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Urban-industrial metabolism within the context of recycling of waste-to-energy residues into construction materials

Study case : the Netherlands

Master's thesis

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Abstract

This thesis investigates the optimization of logistics behind ash transportation from waste-to-energy (WtE) incinerators to cement producers in the Netherlands. The study includes a multifaceted analysis that covers logistic optimization of transports between cities, WtE plants and cement producers' plants. The primary objective is to identify the best connections between cities and plants, to facilitate efficient ash transport, while minimizing environmental impact and costs. To do so, the 12 incinerators present in the Netherlands have been studied, and data regarding their capacity, production of energy, heat, electricity and ash, have been collected.

In a second instance, it has been analyzed the possible outcomes of the policies proposed by the Government and Environmental Organizaions, in accordance with the Green Deal and Circular Economy goals. Therefore, two future scenarios in the same context have been implemented, assuming that the most impactive reason of change will be: recycling goals of the country in regard of Circular Economy, and the growth of the population towards 2050.

The research tools include collection of numbers from data archives, Geographical Information Systems (GIS) and mathematical modeling implemented in Excell.

Last, the results of the optimization will be analyzed to suggest possible improvements of the system, having the goal of consuming less energy and decreases the costs of transportation, furthermore, have a realistic overview of the waste-to-energy scenarios in the next 25 years to better prevent and adapt to the changes.

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Abbreviations

CBS	Central Agency for Statistics
CE	Circular Economy
CSV	Comma-Separated Values
DE	Doughnut Economy
IEA	International Energy Agency
GIS	Geographic Information System
IS	Industrial Symbiosis
MSW	Municipal Solid Waste
SS	Sewage Sludge
WtE	Waste to Energy

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1 Introduction

The World is facing constant population and economic growth, the consequences of which affect the production of waste, which is expected to increase to 3.4 billion tonnes in 2050 [1]. In the European scenario of waste management, the Netherlands locates itself as one of the most advanced countries regarding the application of recycling strategies, waste treatment, and future policy proposals and monitoring. Indeed, the climate ambition in the Amsterdam Coalition Agreement is aiming to decrease of the 55% of emissions by 2030. And to become 100% circular by 2050 [2]. One of the biggest causes regarding waste production, and emissions of CO2, is related to the construction sector, responsible of 39% of it [3]. In this scenario of change towards a circular economy, one discussed topic is the use of ash from incinerators for sustainable cement. With the re-use of the bottom ash produced by the incinerator of Municipal Solid Waste, it is possible to decrease the number of raw materials used for the production of cement, and simultaneously meet the proposal for closing the loop of the product's lifecycle from design to disposal [2]. Although, with the goal of becoming 100 percent circular, the Netherlands is expected to decrease the production of waste and increase the recycling rate, which will have an impact on the incineration rates, and of course on the bottom ash produced, to potentially reuse for sustainable cement. In this thesis, it will analyze the current situation in the Netherlands regarding the treatment and end-of-life of residual solid waste from households to incineration, while addressing the use of ash for cement from a quantitative point of view, to improve its logistic and conclude with an optimization of the transportation. There will be addressed data regarding population, waste production, recycling, incineration rate, and demand for cement. They will be selected from data sources such as Eurostat, CBS, IEA, and scientific articles. The optimized process's analysis and calculation will be divided into two steps: one related to the current situation, and a second forecasting different conditions in 2050. After the optimization, the results will be analyzed, and a possible conclusion to prevent the waste of energy and consumption in transportation to incineration will be proposed.

2 Problem Analysis

This chapter introduces the topic of waste-to-energy incineration and the subsequent use of ash for sustainable cement. It then highlights the problem that has been chosen to focus the research design, exemplified in figure 1.

2.1 The context of WtE in Europe with focus on the Netherlands

In the European context, the Netherlands represents a positive example of what concerns sustainable challenges. New concepts, such as the Circular Economy and Doughnut Economy [2], appeared in the Dutch discourses in the early stages and years, compared to other European countries. This good example is driven by an ambitious mindset shared by its government, and parts of it, such as Rijkswaterstaat [4], the Ministry of Infrastructure and Water Management, as well as thriving cities like Amsterdam [5].

One of the biggest ambitions, convened by the Green Deal, and adopted by the Dutch government, is to become a Circular Economy by 2050. To obtain these results the country must redirect and monitor several policies, including those concerning the end-of-life of materials, and waste management. Regarding waste production, treatment, and disposal, the Netherlands was pursuing audacious goals already in early 2000, by introducing landfill taxes in 1995 and aiming to 50% recycling of waste by 2009 [6]. Unfortunately, not all the aimed targets have been achieved within the proposed time. Additionally, one of the hardest problems to tackle regarding CO2 emissions is the construction sector. Indeed, 39% of the CO2 global emissions are caused by constructions, and 7% of GHG emissions are attributed to cement manufacture [7]. Moreover, The world population is growing, and the increasing trend of moving to cities results in a rising demand for housing and construction materials.

To redirect towards the decarbonization of this sector, industrial symbiosis paths can be implemented by reusing the ash produced by the incinerators for cement production, and closing the open-loop recycling strategy within circular economy settings [7]. The improve-

ment of this solution can help decrease the costs and emissions caused by the linear process, commonly adopted in several countries in Europe. This urban industrial metabolism framework appears promising, but it's leaking in some crucial areas. In the first instance, the lack of collaboration between the actors [7]; and secondly, the possibility that the current conditions will change due to the implementation of more strict policies.
Indeed, in the sustainable hierarchy regarding waste treatment and disposal, as illustrated by the famous Lansink's Ladder [8], the third to last option after incineration and landfill, is energy, namely: producing energy by burning waste(WtE). Moreover, by reaching the aimed percentages of recycling of residual waste in the next years, the production of ash in the Netherlands could decrease drastically, making the substitution less tempting. On the other hand, it is improbable that the production of the so-called non-hazardous waste, that needs to be incinerated and cannot be recycled, would end.
Moreover, as previously mentioned, the Netherlands has been historically ambitious in its goals, and not always the targets have been reached in the suggested timings. Therefore, it is realistic to consider the coexistence of more than one possible scenario.

2.2 Problem formulation: adaptation strategy for waste to energy industry

This thesis aims to tackle the problems introduced in the previous paragraph relative to the development of a close-looped industrial symbiosis between cities, WtE, and cement plants; while adapting to the ambitious targets that this country aims to achieve. Having explained the context of waste incineration and the possible outcomes for reuse of the produced bottom ash for sustainable cement, the main question to be addressed is: how will sustainable cement manufacturing be affected by the increase in recycling, assuming an implemented industrial symbiosis between cities, incineration and cement plants? To be able to analyze and answer the question from beginning to end, the problem will be unwrapped in a selection of 3 subquestions, which will help the development of the thesis and the finding of answers.

2.3 Research question

Considering the Netherlands as one of the most advanced countries in terms of reaching the Green Deal goals, and aiming to be 100% Circular in 2050, how can the waste-to-energy system and the use of ash for sustainable cement be improved to fit the proposals?

Subquestions

- What are the quantities of waste processed, ash, and energy produced nowadays?
- How can the transport system be optimized to obtain a more efficient dialogue between cities and incinerators?
- By predicting future scenarios, is it possible to understand how the country will or will not achieve the aim to be 100% circular, and how this will affect the production of ash for sustainable cement?

RESEARCH QUESTION	
Considering the Netherlands as one of the most advanced countries in terms of reaching the Green Deal goals, and aiming to be 100% Circular in 2050, how can the waste-to-energy system and the use of ash for sustainable cement be improved to fit the proposals?	
SUBQUESTION 1	What are the quantities of waste processed, ash, and energy produced nowadays?
Research of literature and data collection.	
SUBQUESTION 2	How can the transport system be optimized to obtain a more efficient dialogue between cities and incinerators?
Critical analysis of data. Use of Excel to create plausible scenarios of the material flow and transportation in the Netherlands, and calculate optimization of transport. Supportive use of GIS for mapping the results.	
SUBQUESTION 2	By predicting possible scenarios, is it possible to understand how the country will or will not achieve the aim to be 100% circular, and how this will affect the production of ash for sustainable cement?
Collection and use of data with range of possibilities to create two scenarios in 2050. Use of results from previous optimization to calculate possible solutions for the two scenarios.	
Answer to the main question.	

Figure 1: Research design

3 Theoretical framework

Various concepts such as the WtE in Europe and the Netherlands, Circular Economy (CE), and Industrial Symbiosis (IS) appeared during the research. The following section will illustrate these concepts and their theoretical background in the current situation. The theory behind CE and IS will be described as they are fundamental for understanding the concept behind the thesis and its aim. then the situation regarding waste management in the Netherlands will be addressed. Finally the incinerators in the Netherlands will be listed and described individually, as they have been studied in detail concerning their capacity and production, and they play a crucial role in the optimization. Finally, the data used to create the representative 2050 scenarios will be explained to provide a better understanding of their role in the thesis.

3.1 Circular Economy and Industrial Symbiosis in the construction sector

CIRCULAR ECONOMY

Cities play a fundamental role in the Circular Economy (CE) context for their impact on production, consumption, and emissions. In fact, they are responsible for 80% of global natural resources, 50% of global waste, and 75% of GHG [9]. The CE concept has been adopted in many European cities to tackle challenges relative to climate change through strategies such as refuse, reuse, reduce, remanufacture, refurbish, and recycle [9]. This translates into control in the material flow while integrating every process in a close loop, as exemplified in the Fig. 3. Especially since the launch of the European Union's (EU) 2015 CE Action Plan [9], European cities have been front runners in CE implementation. In the urban context, not only the Production Flow is the focus of CE strategies, but also spatial planning and Socio-political structure are integrated in the system, as shown in 2. Among the urban areas that have achieved notable success in the implementation of CE, Amsterdam stands out. the first circular action plan has been proposed in 2012 [9]; in 2016 the government released the programme "A circular economy in the Netherlands by 2050". Lastly, in 2020 the municipality published the newest CE policy: "Amsterdam Circular strategy 2020-2025" [9]. Specifically for waste management, the policies include particular actions in recovery and recycling infrastructures, economy incentives to reduce the non-recyclable waste generation, increasing the efficiency of waste provision, and promoting urban and industrial symbiosis [9].

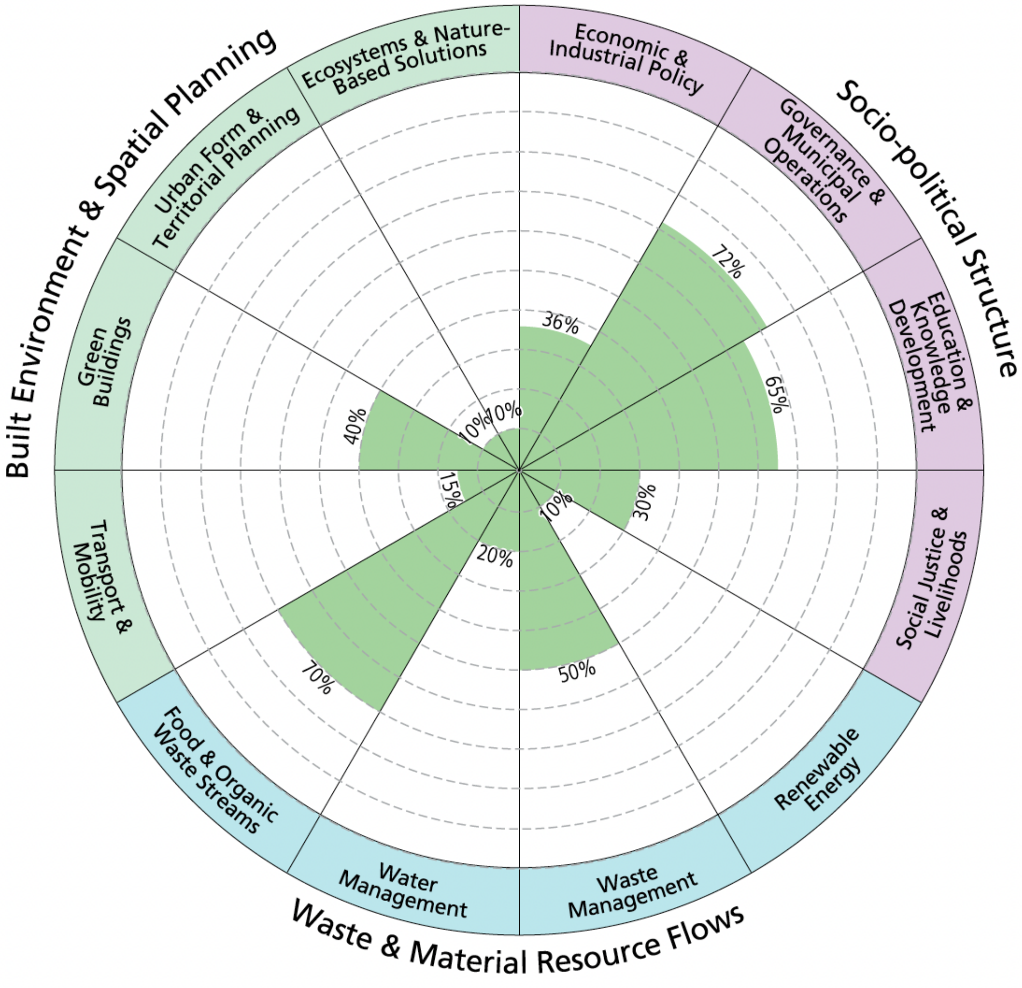


Figure 2: Amsterdam CE strategy [10]

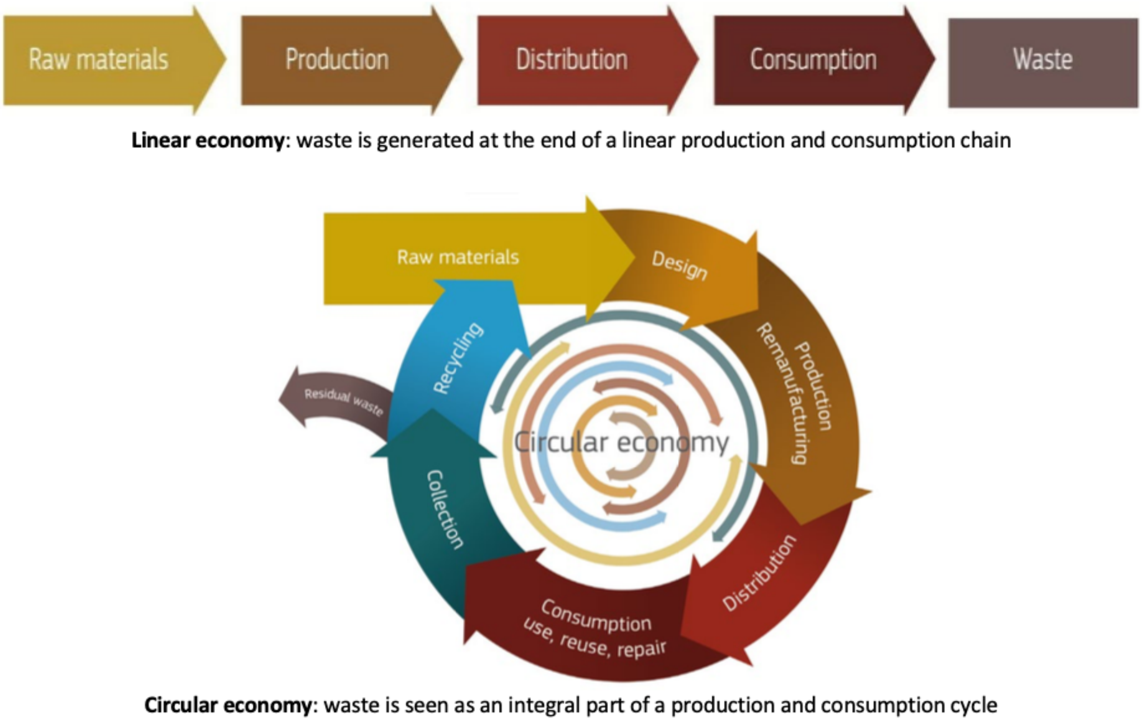


Figure 3: CE diagram [10]

In essence, the CE strives to achieve an integrated understanding of the wider context, including rural and non-urban areas, cities and industries. This objective is to develop an innovative business model that does not compromise the environment, as exemplified by the renowned Butterfly Diagram (Fig.4), designed by Ellen Mac Arthur Foundation in 2019. To do so, it proposes the application of technologies such as industrial symbiosis, reverse logistics, and cleaner production, which focus on the end-of-loop strategies mentioned before [9].

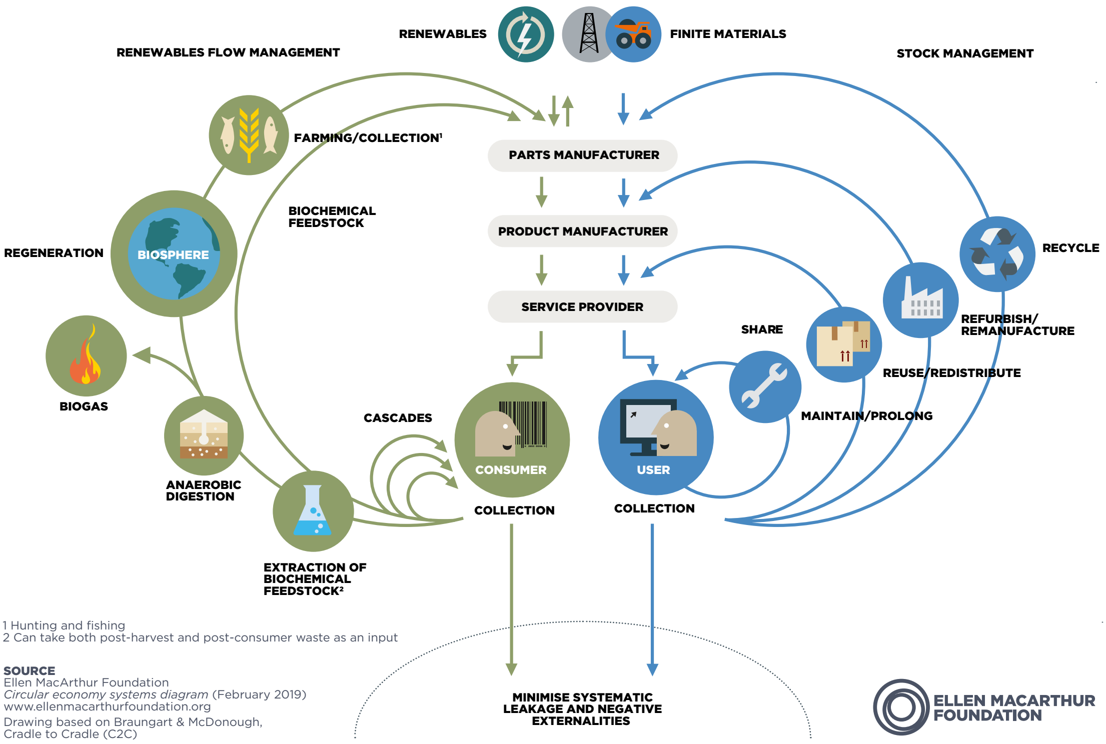


Figure 4: Butterfly Diagram - Elle Mac Arthur Foundation [11]

INDUSTRIAL SYMBIOSIS

The concept of Industrial Symbiosis represents an innovative approach, introduced in the global circular strategies in the early 2000 [12], to not only mitigate environmental impacts but also drive economic growth, based on circular economy theories [9]. At its core, IS seeks to transform linear, wasteful production systems into interconnected networks where waste and by-products from one industry become valuable resources for another, as shown in Fig. 5, thereby minimizing waste generation and maximizing resource efficiency [12]. Adopting this technology makes it possible for the actors involved to close the loop of the material flow of the industrial process and benefit from a mutual exchange in manners of economic and material waste [12].

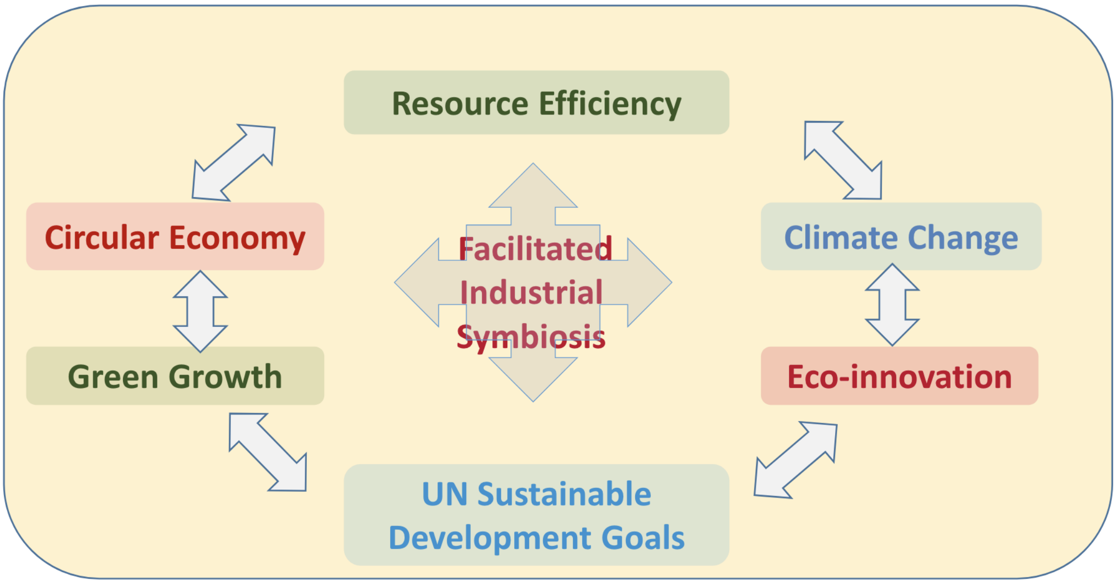


Figure 5: Industrial Symbiosis Diagram from EU circular Talks, International Synergies [10]

INDUSTRIAL SYMBIOSIS IN WTE

Within the context of the WtE process, incinerators produce an important quantity of ash residues, especially bottom ash, which usually correspond to 20 % of the mass of waste incinerated [13]. In the European scenario, it is common practice to incinerate residual solid waste, which brings to the production of 17.6 million tonnes of bottom ash (BA) per year [7]. Without the right regulation, and a quick implementation of industrial symbiosis into the sector [7], the amount of residues often end up in landfills. Solution that is considered, as previously mentioned, the least desirable option for circularity and environmental impact. [8].

Meanwhile, the construction sector is responsible for 39% of global CO_2 emissions [7], and the cement industry alone accounts for 7% of greenhouse gas emissions [14]. In addition, in the cement factory, chemical processes involved in clinker production account for 50% of total CO_2 emissions. [7] Therefore, the market is increasingly exploring alternative sources to the raw materials for decarbonising the process of production, such as Bottom Ash (BA) from WtE incinerators, to reduce its environmental footprint [15]. Indeed, the convergence of waste-to-energy and the use of ash for cement production provides a compelling case study. The use of cement has been subject to an increase in recent years, and with the growing population, and migrations to the cities, demand for cement production is expected to grow in the coming years. While globally the production of cement is expected to increase by 12-13% from the 2014 level by 2050 [16], in the Netherlands, statistics show that the number of businesses in the Netherlands increased from 2010 to 2020 of 61%, and the volume production of the 27% [17]. However, dutch cement production strongly depends on imports as the country has ceased production of clinker. [16]. In fact, in 2019 the dutch imports still covered 54% of the cement consumption [16]. In addition, the country has already adopted decarbonisation strategies such as the use of fly ash produced by the burning of pulverized coal to obtain benefits in terms of the thermal energy required for production. [16]. It is therefore anticipated that the utilization of bottom ash from waste incineration will have a beneficial impact with regard to the decarbonization of production processes, demand of energy and heat reduction both from industries and citizens, thanks to district heating [18], and the promotion of circular technologies.

3.2 Waste production in the Netherlands and WtE: 12 study cases

The production of waste in the Netherlands has been subject to increasing control and monitoring. The implementation of several policies and circular strategies has resulted in a gradual decline in waste production, from 535 kg per capita in 2019 [3](Fig. 6), to 473 kg per capita in 2022 [19]. The percentage of waste recycling appears to be in a range between 60% according to EEA [20], and 79% according to the paper "Factsheet waste and resource management" [4]. As another example of improvement in policy application, Statistics Netherlands (CBS) has reported a 14 % reduction in the use of raw materials in the Dutch economy between the years 2004 and 2014 [21]. However, to meet the needs of the Dutch citizens the raw materials imports have risen. Therefore, the Dutch government aims to reduce their consumptions of 50% by 2030, and become a 100% circular by 2050 [21].

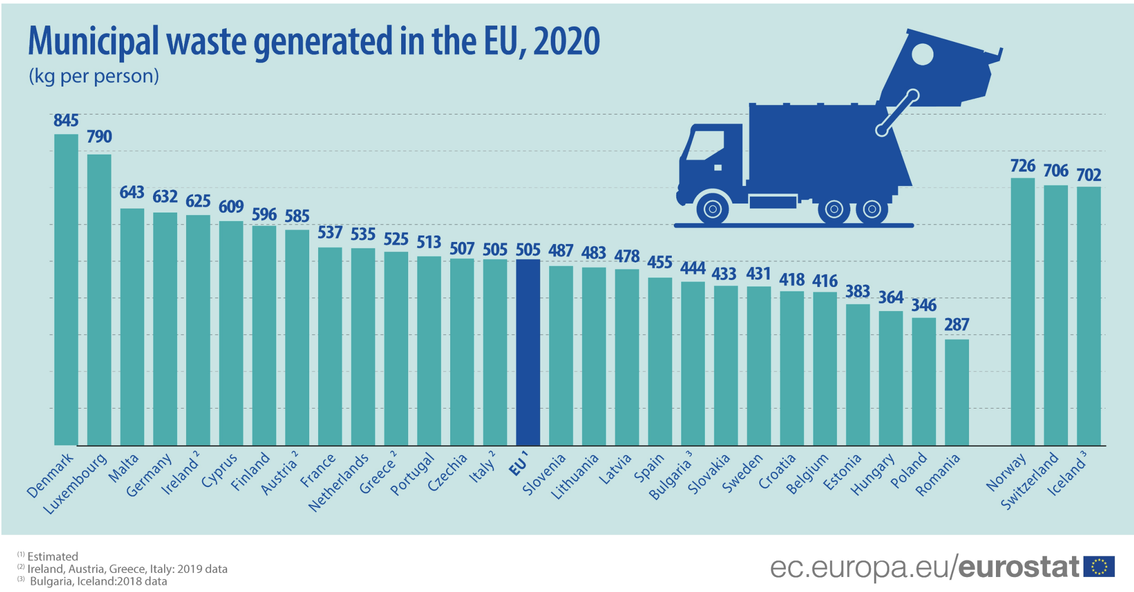


Figure 6: Production of waste in Europe

Landfill taxes were introduced in 1995 in response to an increase in the water level and a consequent decrease in land. The Dutch government gradually increased them until 2010, when landfill taxes in the Netherlands became the highest in Europe. As a result, the recycling rates increased, but the incineration rates remained stable [6]. In the same year, 9.8 million tonnes of municipal solid waste (MSW) were generated, of which 5 million tonnes were recycled, 3.2 million tonnes were incinerated, and 0.03 million tonnes were disposed of in landfills, as illustrated in the graph in Fig. 7 [6]. The tax rate is not limited to landfills. In the Netherlands, the disposal tax is equal for both landfilling and incineration (33.58 EUR/t)[22]. Furthermore, the tax is applied to waste exported from the Netherlands for landfill or incineration in other countries, thereby discouraging the export of residual municipal waste. In 2019 the Netherlands placed a significant 42% disposal volume of municipal waste into incineration [22].

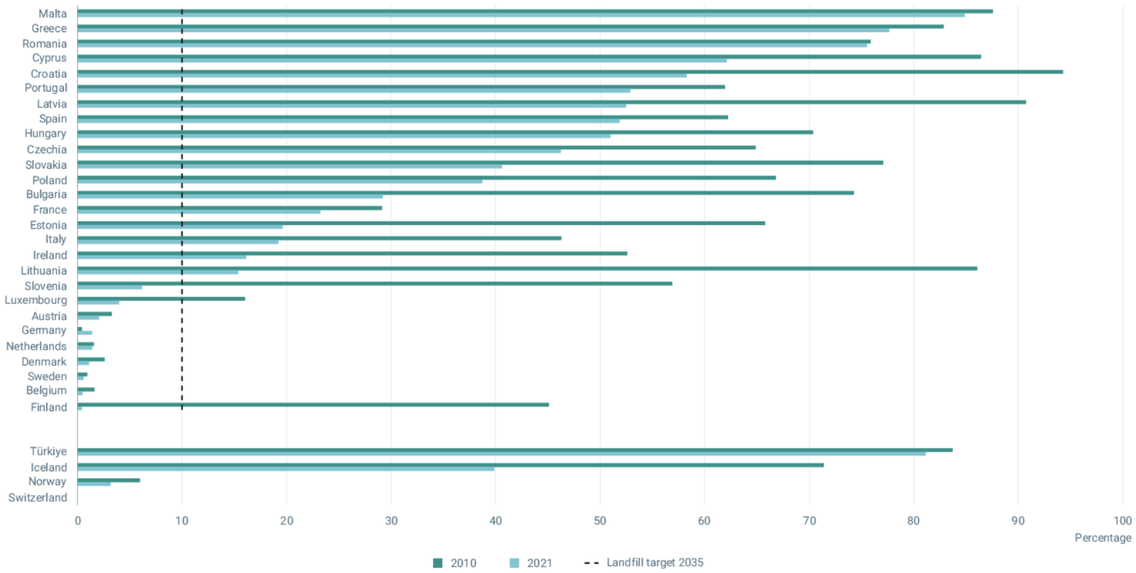


Figure 7: Municipal waste landfill rates in Europe [20]

In 2020 the Dutch new target was to achieve the 65% recycling of waste by 2025 [22]. To assess the effectiveness of the policies, Rijkswaterstaat monitors the quantitative and qualitative aspects of waste streams, the movement of waste across borders, the activities of waste treatment facilities, and developments in the international waste management market [4]. The recycling rate registered in 2021 by the EEA reached 57.8% [20] as showed in Fig. 8, while the incinerators have been stable at around 41.8%, for a total production of 3436 thousand tonnes in 2022 [3]. These data will be used for the optimization process shown in the next chapter.

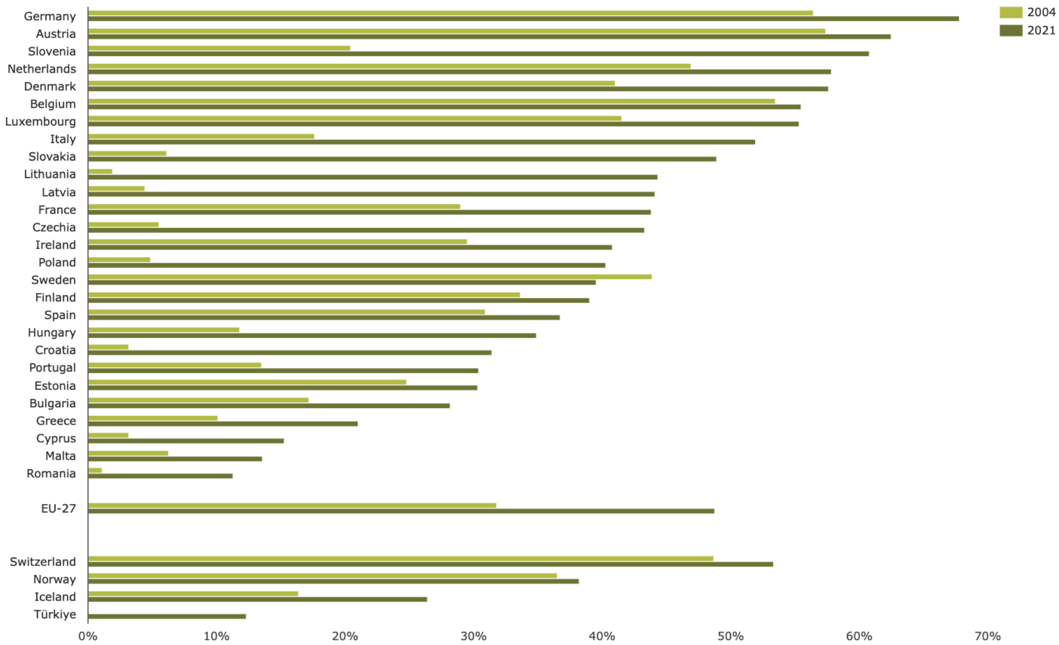


Figure 8: Residual waste recycling rates in Europe [20]

A total of 12 waste-to-energy incinerators are currently operational in the Netherlands. Data about the incinerators' capacity, waste processing, and ash production have been analyzed. The information was identified from various sources such as articles, websites of the incinerators, and annual reports. However, for some of the incinerators, data were not readily available, necessitating using the paper "Decarbonization option for Dutch waste incineration industry" [15] as a reference.

The paper [15] shows a map of incinerators (Fig. 9) which has been useful for the research to not start from scratch. Consequently, a brief overview will be provided of the incinerators identified in the paper and from other sources, with the aim of providing an understanding of their geographical distribution within the waste-to-energy market. Following an investigation into the Dutch incinerators, it has been determined that the majority of WtE incinerators in the Netherlands process more than one typology. Indeed, the majority of these incinerators process and burn biomass or sewage sludges, in addition to municipal solid waste [15].

Figure 9: 12 incinerators MSW, SS and Biomass [15]

Following is the list of WtE incinerators, objects of the research, and sources of data useful for the optimization. A brief description of them will follow, to have an overview of their role in the waste and incineration sector in the Netherlands. It should be noted that not all of the incinerators, and their attributes, correspond to those in the source document. Indeed, the paper was used whenever the websites or reports published by the incinerators were not sufficiently informative or reliable. Moreover, in some other papers, 13 incinerators are mentioned [23]. Therefore, it has been decided to follow the structure of the source to keep consistency and use the information published by the companies, when available.

Incinerators:

1. AEB(AEC/HRC Amsterdam)
2. Attero Moerdijk (AEC)
3. ARN B.V.

2(2). Attero Noord B.V. GAVI Wijster

4. AVR Afvalverwerking B.V.(Rozemburg)
5. AVR-Waste (Duiven)
6. EEW Delfzijl B.V.
7. HVCafvalcentrale, Alkmaar
8. HVCafvalcentrale, Dordrecht

8(2). HVCafvalcentrale, Dordrecht

9. PreZero ReEnergy
10. REC Harlingen
11. SNB Moerdijk
12. Twence Afval en energie

1. AEB(AEC/HRC Amsterdam)

One of the most important and old incinerators in the Netherlands. It is composed of 6 furnaces, distributed in the two headquarters: four in the Afval Energie Centrale (AEC), and two in the more modern Hoog Rendement Centrale (HRC) [18]. With one tonne of waste, 628 kWh of electricity and 208 kWh of heat are generated. This energy is used to supply heat to 30,000 houses in the North of Amsterdam. Daily, 500 trucks bring waste from the city to waste processors and incinerators, collecting and processing a total amount of 1.4 million tons of waste per year [18]. Around 1 million tons of waste is redirected to incineration without prior separation [18]. AEB receives around 300,000 tons of household waste per year from the Amsterdam Region. Approximately 15% of this household waste is recovered through a materials recovery facility (MRF) which separates plastics, paper, metal, and six other waste streams [18]. With its main competitor AVR (4,5), the two companies account for 39% of the country's waste energy capacity [24].

2. Attero Moerdijk (AEC), Attero Noord B.V. GAVI Wijster

Attero processes around 1.8 million waste per year, of which plastic, beverage cartons, and metal through post-collection separation [25]. The two plants owned by the company generate 800 GWh of renewable electricity, equivalent to powering 300,000 homes, as well as 22 m3 of green gas [25]. The largest plant is located in Moerdijk. This plant switches flexibly between the production of renewable electricity, and sustainable heat for the industrial sector and future heat grids. This plant has been in operation since 1997 and was expanded with a fourth incineration line in 2008 [26]. The plant converts 1 million tons of household and similar commercial waste from the Netherlands, England, and Ireland into energy every year. The waste is brought in by trucks and ships. [25]. The second plant is located in Wijster, where both raw materials and energy from waste are produced. In Wijster, also renewable electricity and heat are produced [25]. As an integrated platform, Attero is one of the contributors to the Dutch and European circular economy targets, and for the energy transition. It also helps to address the energy independence and decarbonization challenges in the Netherlands [26].

3. ARN B.V.

The ARN waste-to-energy plant, which started in 1987, incinerates 300,000 tons of (non-recyclable) household and commercial waste annually. [27]. The waste-to-energy plant supplies approximately 150,000 MWh of electricity to the public grid and 800 Tj of heat per year [27]. Moreover, it supplies heat to 6,400 homes in the new-build districts Waalsprong and Waalfront in Nijmegen [27]. No further information has been located regarding this incinerator. Therefore, all the data used for the optimization have been taken from the source [15].

4. AVR Afvalverwerking B.V.(Rozemburg), AVR-Waste (Duiven)

The company asserts that it is the largest waste processor in the Netherlands. The company's objective is to continue to expand as an independent entity, aiming to become one of the three largest waste and environmental management groups in the Netherlands, and Europe [27]. The plant has an incineration capacity of some 1.8 million tons of domestic and industrial waste, and 200.000 tons of hazardous waste annually [28]. Moreover, 3225 GigaW/h electricity is generated from waste in the Netherlands, sufficient electricity for the needs of 1.100.000 families [27]. Furthermore, approximately 350,000 tons of residue materials from waste incineration at AVR are utilized for the construction of the Dutch road network, among other applications [28]. AVR is also one of the largest sustainable district heat producers. In 2020, it supplied over 5.4 PJ of heat to district heat networks in Rotterdam and the Arnhem region. This considerable volume of heat is distributed to approximately 160,000 homes connected to one of the Vattenfall, Eneco, or WBR heat networks [28]. The waste-to-energy plants recover raw materials and produce energy. A total of ten ovens are distributed across the Rozenburg and Duiven locations [29]. The term "residual waste" encompasses a multitude of forms and states. One example is liquid. Indeed, the highly contaminated waters from the sewage sludges cannot be processed in biological water treatment plants, therefore, these wastewaters are instead processed and then burned in the WtE plant. The plan can process this wastewater thermally in four vortex furnaces, which together can handle 325,000 tons per year [28]. The main data are shown in their annual report as illustrated in Fig. 10.

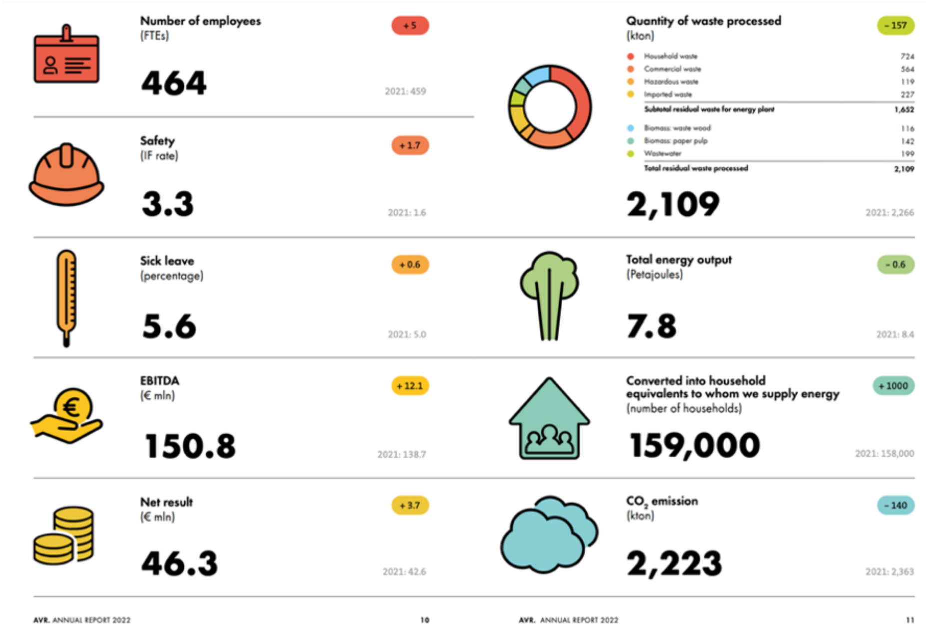


Figure 10: AVR Report info

6.EEW Delfzijl B.V.

Not information has been roundabout this incinerator. The data has been based on the reference [15].

7. HVCafvalcentrale, Alkmaar, Dordrecht

HVC's plants employ sustainable heat sources to the greatest extent possible in order to feed the heating networks. Furthermore, they are investigating the potential for further enhancing the sustainability of existing sources [30]. They are engaged in the construction of new heating networks and the expansion of existing heating networks [30]. The website does not provide much information about the capacity and energy produced or waste processed, as Fig. 11. However, it does demonstrate a strong commitment to the social aspect, including initiatives such as teaching recycling techniques, organizing workshops, and making waste treatment and incineration processes visually clear [30].

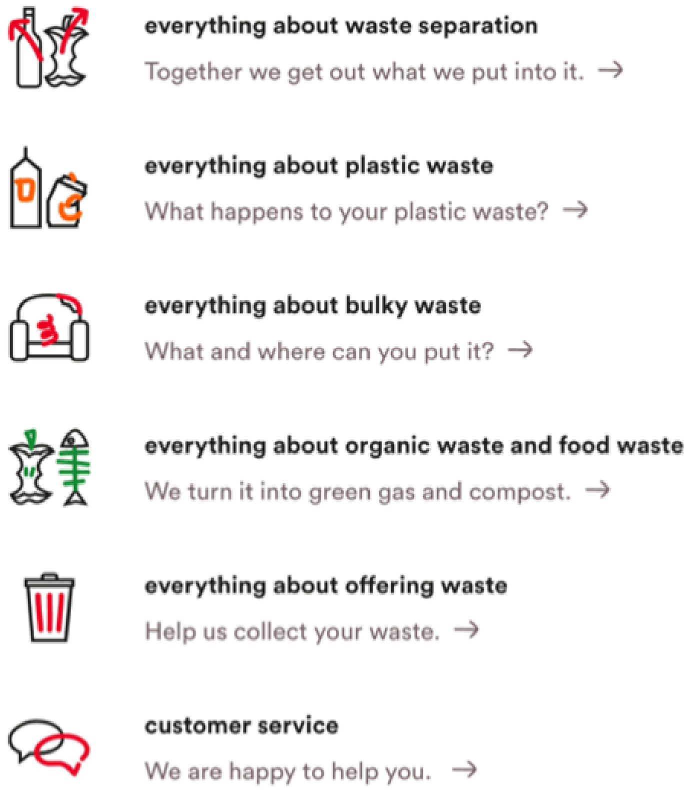


Figure 11: HVC waste separation guide

Moreover, in the second plant, also Sewage Sludges are incinerated. The process of drying and incineration of the SS is described n the website: "We dry the wet sewage sludge from our shareholding water boards in the sludge processing plant. We remove about half of the water with this. We burn the dried sludge. We use the heat released to dry the sewage sludge. We capture the warm vapors released during drying and supply them as heat to the Dordrecht district heating network." [31]. The construction of the Dordrecht heating network started in approximately 2013. The initial phase of the project involved the connection of 210 newly constructed residential properties (the Nassau complex on the Singel) and the Energy House [31]. The warm vapors that were previously blown away, are now captured by an adjustment in the installation and converted into heat for the heating network. This is heat that would otherwise be dissipated during the processing phase. Consequently, the sludge processing plant provides additional capacity to provide 7,000 households with 100% sustainable heat. The dried sludge is incinerated to generate sustainable electricity [31].

9. PreZero ReEnergy

The ReEnergy plant is one of the most contemporary waste-to-energy facilities in Europe. ReEnergy is at the vanguard of environmental performance. With a treatment capacity of 291,000 tons per year, the plant is capable of processing municipal and commercial waste and generating 275,000 MWh of electricity annually, which is sufficient to supply 70,000 households [32].

The waste is transported by truck to the delivery hall of the WtE plant, where it is poured into the bunker. The bunker has a capacity of 7,000 tons, which is sufficient for five days of continuous operation. The waste is burned on a grate with five zones, the first two of which are water-cooled. During this combustion process, the volume of the waste is reduced by 90% [33]. The residual ash is subsequently separated from the bottom ash, with the latter being reused for embankments and foundations. Every step of the process is clearly shown in the explanatory drawing of their website reported in Fig. 12. The state-of-the-art plant is designed to meet the most rigorous European standards for the utilization of energy and the efficiency of power plants, particularly following the Waste Framework Directive R1 formula [32].

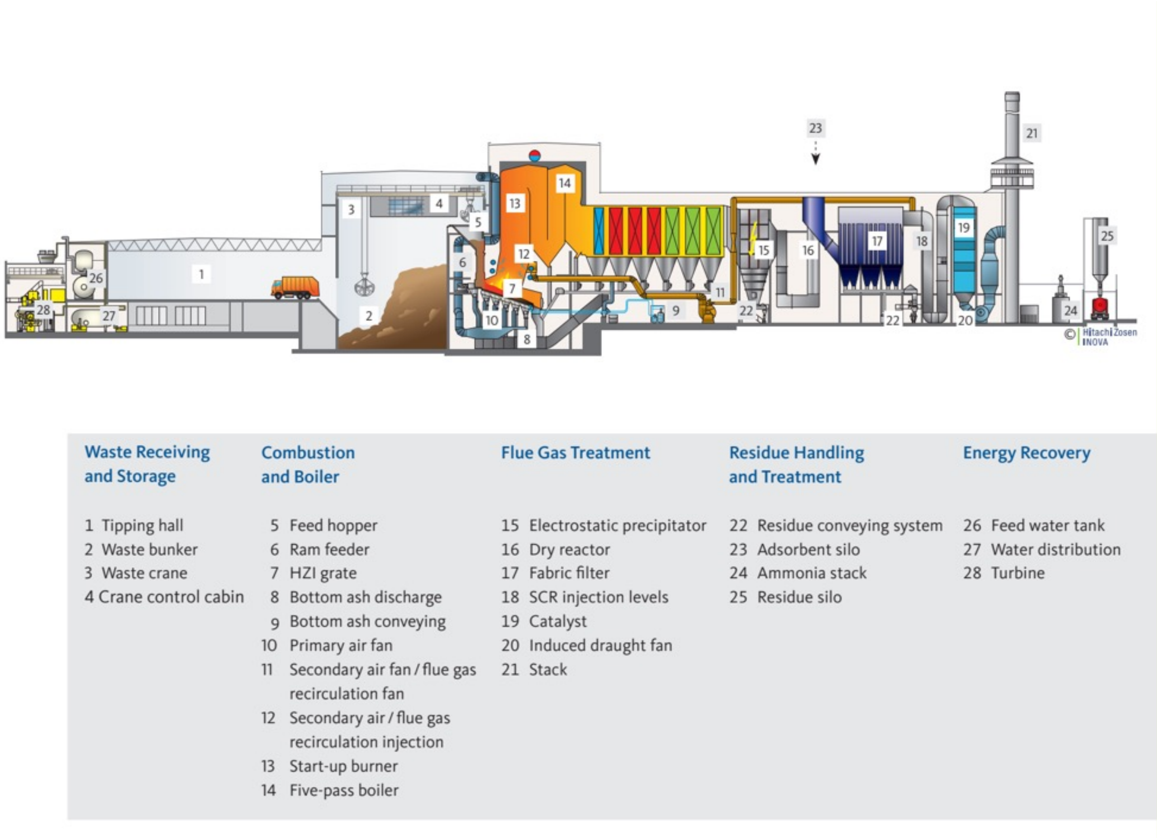


Figure 12: ReEnergy WtE incineration process [32]

10. REC Harlingen

One of the newest plants in the Netherlands is scheduled to treat 210 thousand tonnes per year of waste. The total waste is from 36 municipalities and 173 thousand households. However, no further information has been found. The rest of the numeric data useful for the optimization will be taken by the source [15].

11. SNB Moerdijk

The Dutch water authorities operate two sludge incineration facilities, with a combined capacity of approximately 700,000 tons of wet sludge per year. The remaining 700,000 tons of wet sludges are separated, dried, and co-incinerated in waste-to-energy plants or composted and co-incinerated in the Netherlands, or surrounding countries. SNB, in conjunction with the previously mentioned HVC, has been the proprietor and operator of the two incineration facilities in Dordrecht (Zuid Holland province) and Moerdijk (Brabant province) since the early 1990s [34].

SNB incinerated approximately 420,000 tons. The quantity of ashes resulting from the incineration of sludge at HVC and SNB has decreased slightly, by approximately 10% over the past decade (Fig. 13). This is attributed to a slight increase in the organic content of the sludge, despite an increase in the digestion and biogas production of the water authorities [34].

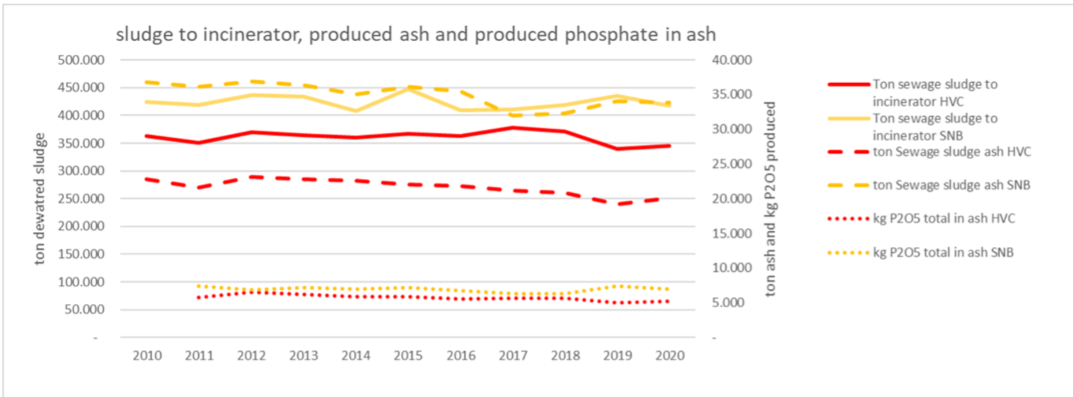


Figure 13: HVC and SNB quantities [35]

The sludge is subsequently stored in four dedicated storage bunkers. In total, the storage capacity of these bunkers is 16,000 tonnes. This storage capacity allows SNB to store sludge in an environmentally responsible manner. Furthermore, it enables an effective response to fluctuations in the sludge supply and processing capacity [34].

The sustainability process continues to be increasingly developed. For example, the valuable phosphate from the fly ash is now partly reused as a raw material for fertilizer.

It is also being investigated whether wastewater can be converted back into process water [34]. The SNB processes sewage sludge for water boards. Approximately 410,000 tons of dewatered sewage sludge are processed annually, which corresponds to 30% of the total sludge supply in the Netherlands. The SNB's mono-incineration plant on Moerdijk (Fig. 14) is the largest in Western Europe. As a result, the Netherlands is internationally regarded as a leader in the field of sludge processing technology [34]. Incineration is currently the most effective method for the destruction of unwanted substances in sewage sludge. SNB endeavors to achieve this in a sustainable manner, although combustion inevitably releases substances such as flue gases and ash residues. Indeed, phosphate from the fly ash is now partly reused as a raw material for fertilizer [34], and ash can be reused for cement production [16].

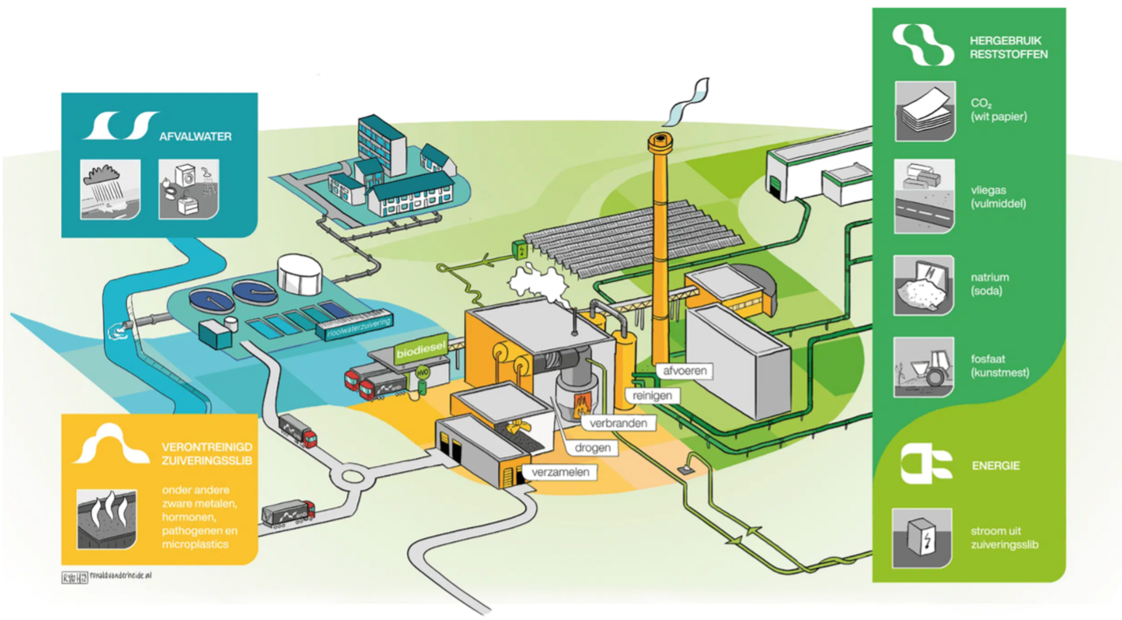


Figure 14: SNB plan: map and overview [34]

12. Twence Afval en energie

Twence is a waste-to-energy company based in Hengelo, in the Netherlands. The company operates a large amount of waste throughout several regions. The company operates a CO2 capture plant that treats a slipstream of one of its waste incinerators, with a current capacity of 5 tons of CO2 per day. The CO2 is currently used for bicarbonate production [36]. Waste that cannot be further sorted or recycled is transported from the waste separation plant to the waste-to-energy plant. Following incineration, the resulting bottom ash is processed in the bottom ash plant into new raw materials. The incineration process generates energy, which is converted by the plant into sustainable energy in the form of steam, hot water, and electricity for the region [37]. In the bottom ash washing facility, metals extracted from the bottom ash are converted into inert material suitable for reuse in practical applications. One such application is the foundation of road construction. By processing bottom ash from waste-to-energy and biomass power plants, it is possible to recover 90% of ferrous metals and 85% of non-ferrous metals, including copper, aluminum, and zinc [37].
In total, 533 GWh of sustainable heating and 169 GWh of sustainable electricity were supplied in 2020 by the company. This is comparable to the annual energy consumption of 198,300 households [36]. The utilization of bottom ash as a foundation material in the construction of new roads has the potential to reduce the demand for primary raw materials such as sand and gravel, thereby avoiding the depletion of large sand and gravel extraction areas [36].

In conclusion of the theoretical listing of incinerators, Fig.15 represents the data collected and compared, including waste incineration capacity, ash, heat and energy production, and the number of households benefiting from each plant.

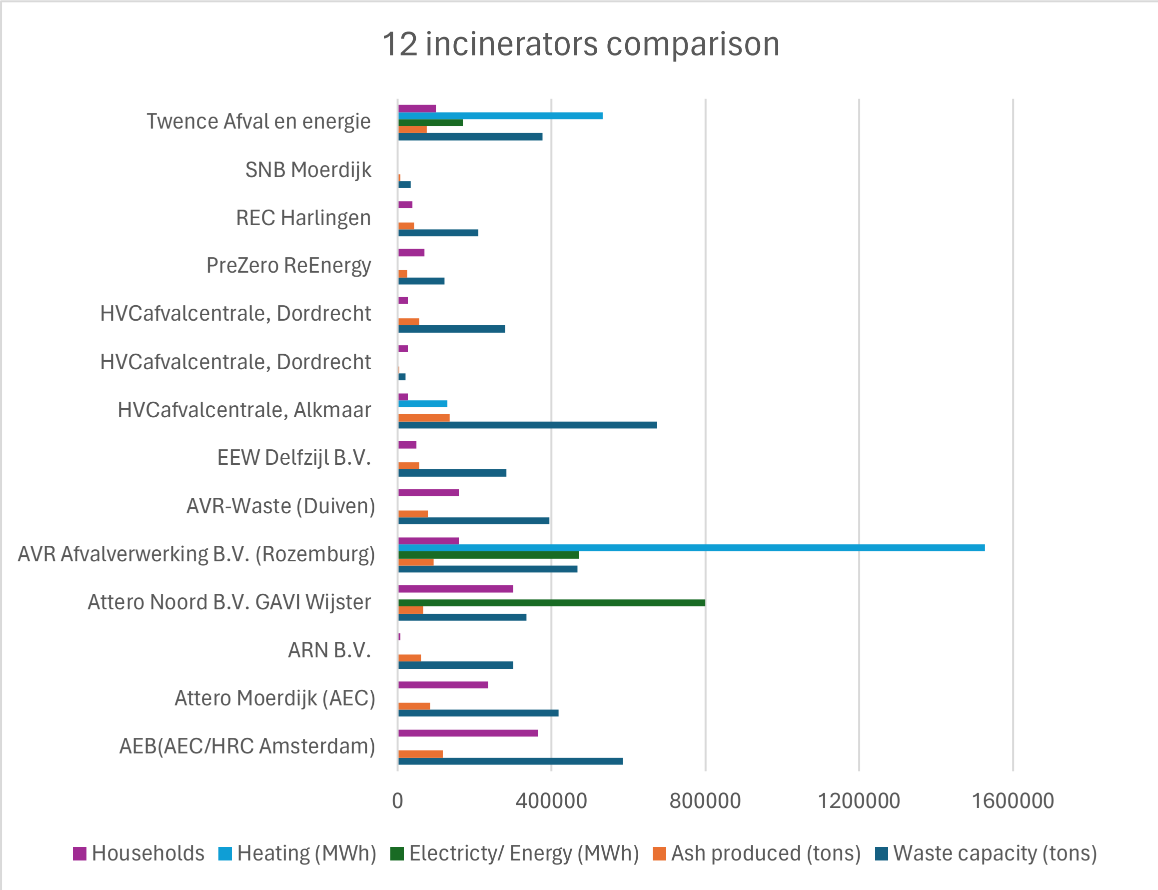


Figure 15: Comparison incinerators features

3.3 Demography changes: creation of scenarios

To create the scenarios, both present and future, data about the population and the forecast for future demographic density in the Netherlands have been collected. Some sources have been used for the generation of the scenarios. The following paragraphs will address information about population growth and its impact on cement demand. As the sources found may not be entirely reliable due to discrepancies in reported results, the data were analyzed and interpreted. This analysis led to the creation of two different scenarios. The map representing the population in 2024 is presented below (Fig. 16).

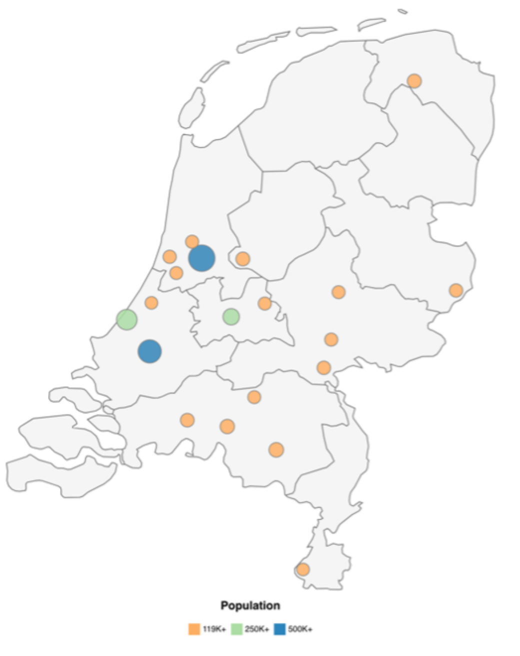


Figure 16: Population 2024 Netherlands [38]

A review of the available literature suggests that the population is expected to reach 19 million inhabitants due to immigration and longevity reasons (Fig. 17). However, CBS [39] suggests that the population may remain stable. This is due to a peak in immigration rates in 2021, which was caused by the War in Ukraine [38]. Consequently, it is less probable that the same phenomenon will occur again shortly. Therefore, two opposite possibilities have been considered, as illustrated in the graph Fig. 18.

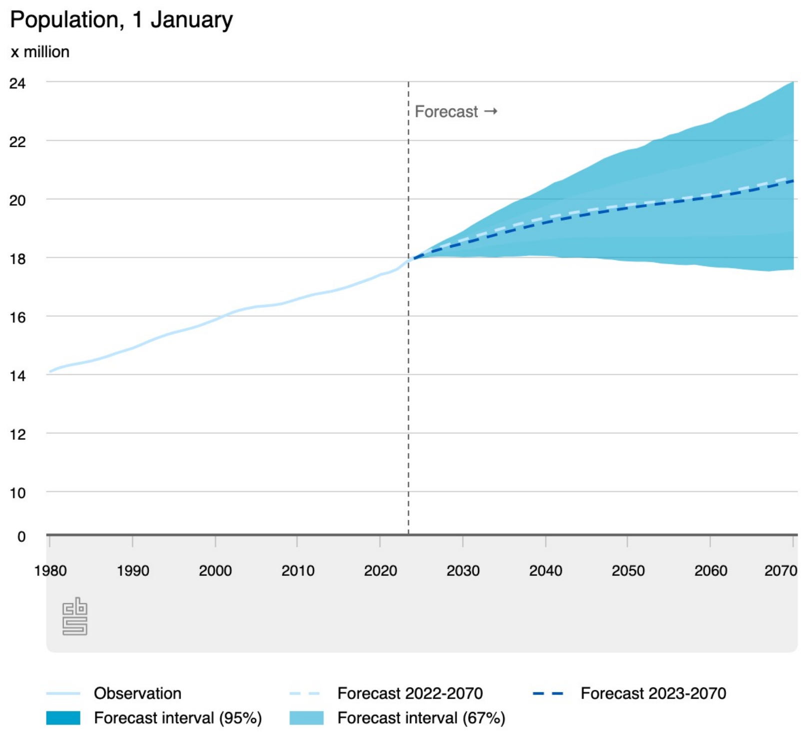


Figure 17: Forecast 2050 of population growth in the Netherlands [39]

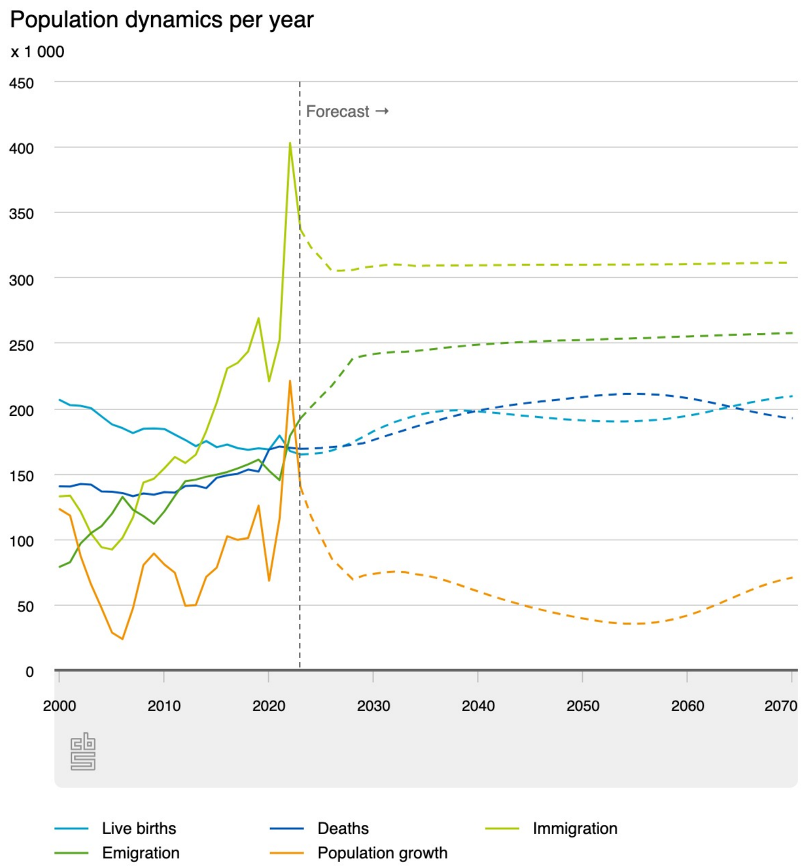


Figure 18: Forecast 2050 of population dynamics in the Netherlands [39]

The scenarios for 2050, as well as changes in demography, will be derived from assumptions that have been calculated based on the data presented above 17, 18. Due to several factors, it has been concluded that the population could grow or remain stable, as mentioned above. It has been decided, therefore, to consider two scenarios regarding the population: one where the population in 2050 is considered to be the same as in 2024, so 17 million inhabitants. A second scenario assumes that the population will grow as projected in 17, reaching 19 million citizens in the next two decades [39].

In the next chapter, the methodology adopted for the setting of the scenarios, and the calculation of the transport optimization, will be explained.

4 Methodology

This chapter explains the methodology employed for the multi-objective linear optimization, which was used to identify the optimal connection between the cities and the incinerators. The objective of this calculation was to enhance the system and to accommodate potential changes that may occur over the next 25 years. The research has been structured in three main steps:

- data collection
- mapping and matrix production
- estimation of scenarios
- calculation of optimization.

In the next paragraphs, the three steps will be exemplified to comprehend the results shown in the next chapter. Sources of the data collected have been displayed in the previous chapter, while maps and data will be displayed together with the results.

4.1 Data collection

Following a review of pertinent literature, all data were collected in Excel. A comprehensive data set was assembled on population, waste consumption, cement production, and energy usage, along with the geographical locations of urban areas, to provide a detailed geolocalisation and quantification of waste management in the Netherlands. For each city, the data previously listed was either identified and extracted or estimated. When calculated, the consumption or production of waste was taken from data archives as Eurostat [3] or CBS [21], to then be divided for the total population of the Netherlands, and consequently multiplied for the population of each city. Respectively, the obtained figures are not representative of the country's entire population. Nevertheless, they correspond to approximately one-third of the total population and, thus, have been selected as a representative example, assuming that the model can be replicated by counting the entire Dutch population. 36 cities have been chosen for the assumptions and the creation of scenarios. The reason is that the Netherlands has a dense population rate [39], therefore it would have been unproductive to include every city in the calculation. Furthermore, by selecting urban agglomerations with a population exceeding 75,000 inhabitants, it has been possible to identify data about the relative cities or to estimate the remaining data points based on the provided data, as illustrated in Fig. 19.

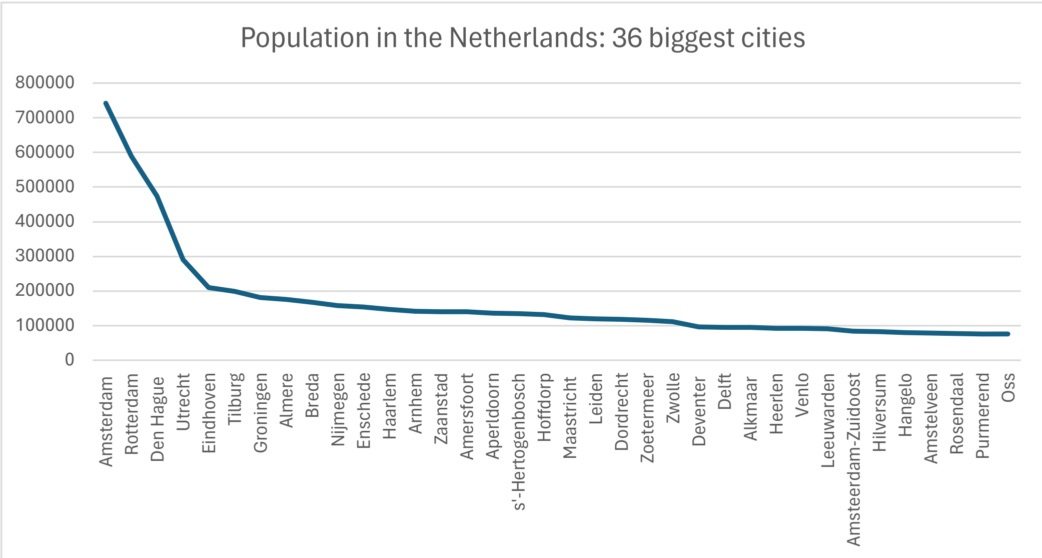


Figure 19: Population of 36 cities in the Netherlands.

Concerning the incinerators, as indicated in the previous chapter, the numbers regarding the plants in operation are the result of a synthesis of data from the paper used as the main source [15], and the ones from the reports submitted by each incinerator found, where available. Similarly to the cities, the incinerators have been mapped, considering data about their typology, incineration capacity, and ash production to differentiate them visually.

The lack of detail in some sources, and the contradiction between the main source "Decarbonisation Options for the Dutch Waste Incineration Industry" (2012) [15], has led to discrepancies in the number of incinerators. The reason for the asynchrony is likely to be that the content's update of the source dates back to 2012, which results in the content being out of date compared to other documents. Nevertheless, it is the more reliable source. The article analyses 12 incinerators, while other sources mention 13 of them, and 14 are shown in the graph. To maintain consistency, it was decided to retain 12 incinerators at the theoretical level and 14 at the numeric level, meaning that it is considered a list of 12 companies, and 14 plants, as shown in Fig. 20.

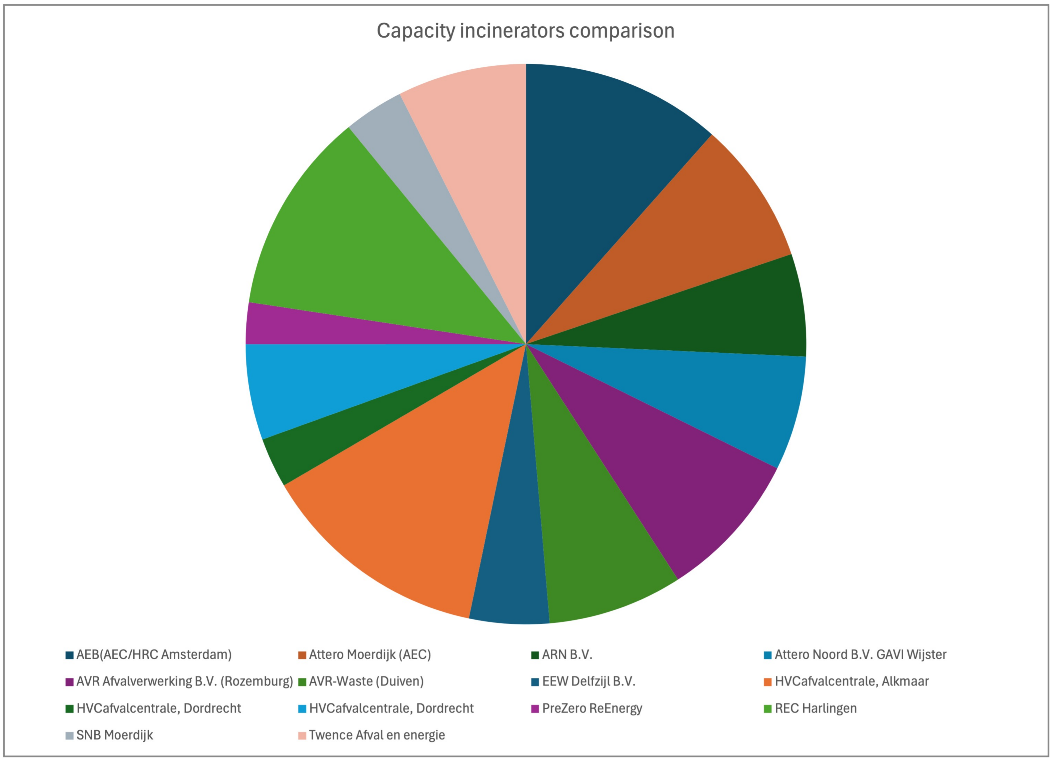


Figure 20: Capacity of Incinerators.

This was necessary because some of the incinerators must be differentiated for their location, type (SS, biomass, MSW), and capacity for a more accurate result of the optimization. Consequently, the list in the theoretical framework collects some of the incinerators under the same name, while in the maps they have been considered as separate.

Thus, after collecting the incinerators, their location and capabilities, dividing the capacity of the furnaces in typology as mentioned earlier, has been attributed to each one the heat and electricity produced and the number of households that benefit from that. However, these data have not been included in the optimization, due to lack of time.

Regarding the production of ash, crucial for the calculation, it has been assumed by considering an average of 20% of the mass of waste incinerated [3] as shown in Fig. 21. The demand for ash in urban areas, which is contingent upon the demand for cement, has been quantified by calculating the percentage of cement consumption observed in the sources. According to the paper 'Decarbonization option for the Dutch cement industry' [16], the cement trade in 2021 in the Netherlands is equal to 5 million tonnes [16]. Of which, only 2 million tonnes are produced inside the country, while 3 million tonnes are imported [16]. Therefore, this is another reason to promote the use of ash from incinerators for cement production. Similarly to the other parameters, these data have been divided for the population of the whole country and multiplied for the inhabitants of each city. Once the assumed cement demand for each city has ben found, the equivalent of the 20% corresponds to the demand for ash taken into account for the optimization.

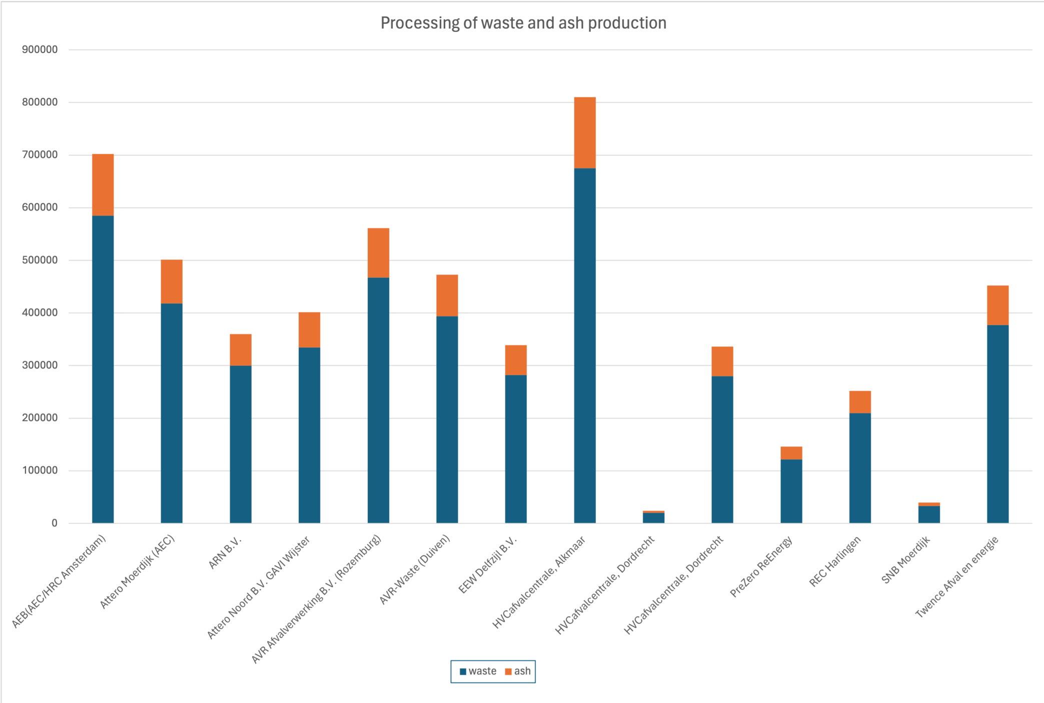


Figure 21: Ash production from waste.

4.2 Mapping and matrices production

Upon the completion of the data collection and grouping to have a holistic view of Dutch waste management in tables, and the creation of the present scenario, the subsequent step is to map the data elaborated. Therefore data have been imported in GIS, which serves to provide a graphical and transparent representation of these variables as reported in Fig. 22. The map represents the 36 cities in analysis (red circles), and the 14 incinerators (triangles). The incinerators have been divided per type by differentiating them per color: white for ss, dark brown for biomass, and beige for msw. As mentioned in the previous paragraph, on a numerical level 14 are the incinerators analyzed, but some of those plants are located in the same place. Indeed, in the graphic representation, some of them are overlapping, therefore only 12 of them are visible.

Once the mapping is complete, matrices can then be generated.

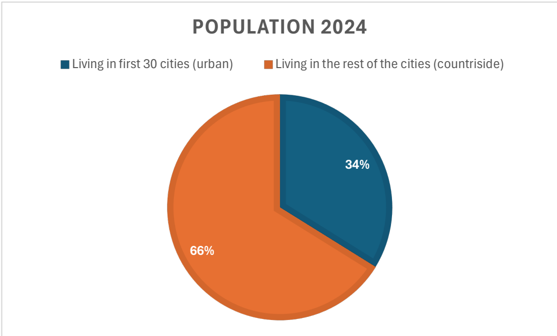
Figure 22: Map of Dutch incinerators and study cases cities.

GIS creates matrices of the CSV selected (incinerators and cities) to find the distances from each incinerator to each city. Once those distances have been estimated, the matrices are exported to then start the optimization process in Excel. Three matrices have been generated: for SS, MSW, and Biomass incinerators. Nevertheless, in the subsequent stages, the matrices will be combined to form a unified system. The matrices play a key role in the calculation process, with the objective of identifying the optimal distances between the study cases. This is achieved through a process of linear optimization, whereby the capacities and production of cement and demand for ash are considered, in order to ascertain the best possible connection between the cities and the incinerators.

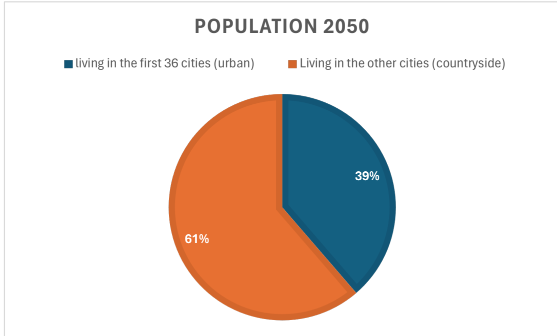
4.3 Scenarios 2050 generation

Before embarking on a detailed account of the optimization process it is necessary to elucidate the methodology used to construct the future scenarios and the rationale behind this approach. As previously stated, the reason for creating the future scenarios is the projected growth in the population of the Netherlands and the anticipated improvement in waste management as a consequence of policies and more stringent recycling regulations. Therefore, following the optimization of the transport for the supply chain of waste and ash residues, it becomes necessary to consider the future in light of the multitude of changes that have been identified.

Once again the data involved are a result of a combination of given numbers and assumptions. Data relative to the first 10 biggest cities in the Netherlands [40], and the overall growth of population [39] have been collected. As previously stated, the cities included in the analysis represent 34% of the population (Fig. 23a). The difference between the actual and projected population, minus the sum of the projected inhabitants of the first 10 cities in 2050 [40], brought to the amount of increased population to distribute between the 26 cities and the rest of the country. One of the reasons why the population will grow is due to immigration [39]. Given that cities are a common target for immigration waves, it is more probable that the initial 10 cities will be more significantly impacted by these figures than rural areas. As a result, in the second scenario, the population living in the case-study cities raised to 39% as represented in the Fig. 23b.



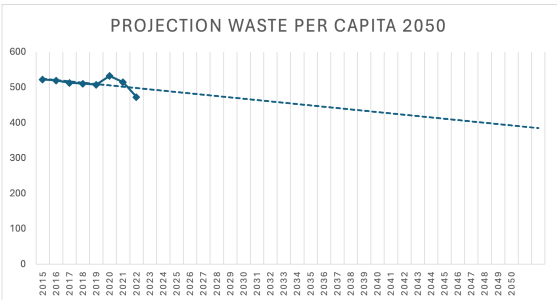
(a) 2024



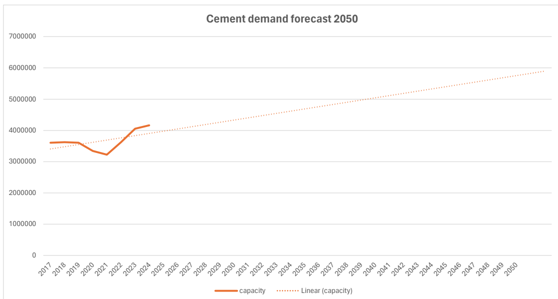
(b) 2050

Figure 23: Chart population for 2024 and 2050 in cities

Coherently with the present scenario, to obtain the consumptions of cement and ash, and the production of waste from each city, assumptions have been made. Indeed, data relative to the recycling rates in 2050 have been collected, as well as the consumption of cement. However, to arrive at specific numbers regarding the waste produced per capita and cement demand in 2050, a forecasting tool has been used to generate predictions based on the data, as shown in the graphs in Fig. 23. In conclusion, has been assumed that in 2050 the consumption of waste per capita will be equal to 375kg/cap, and 5700000 tonnes of cement.



(a) Waste



(b) Cement

Figure 24: Forecast of waste production and cement demand per capita in 2050

To obtain a more accurate representation of the results, it has been deemed necessary to consider two distinct scenarios: a positive one and a negative one. The positive scenario (1) assumes a static population, with the policies for recycling waste being implemented successfully, leading to a recycling rate of 75%. The negative scenario (2) assumes a growing population and a stable recycling rate. This indicates that the implemented policies have not been as effective as anticipated, directly influencing waste production alongside population growth. The consequence of the second scenario would be an increase in waste treatment and incineration. In terms of cement production, the production would benefit from the substitution of raw materials with recycled ones. However, the country's goal is to become 100% circular [5], which makes this option preferable to landfill, but it would still be considered one of the least desirable options according to the Lansink's ladder [8]. Once the two scenarios and their data regarding consumption and demand are completed, their values have been imported into the optimization as well as the data from 2024.

4.4 Optimization

In this section, the unfolding of calculations for the multi-objective optimization will be addressed. The mathematical optimization model has been taken from the paper "Optimal supply chain networks for waste materials used in alkali-activated concrete fostering circular economy" [7]. The model has been previously set up in GAMS, by programming two objective functions that aim to improve the transportation network connected with waste recycling and concrete production [13], to minimize costs and environmental impact. However, in this thesis, only cities and incinerators have been included. A hypothetical scenario has been proposed wherein the demand for cement from each urban center would be met by transporting the ash to the town itself, rather than to a third location, namely the cement plant. The optimization process has been divided into six distinct calculations. The first three are concerned with optimizing waste transportation from cities to incinerators in the present scenario, and the two future scenarios in 2050. The remaining three calculations focus on optimizing ash transportation to the cities.

Once the first networks have been optimized, it was possible to observe that the capacity used by each incinerator was not being fulfilled, particularly in the first scenario of 2050 (1). These results influenced the calculation of the other three optimizations, from incinerators to cities. The second step was driven by two main purposes. The initial target was to ascertain whether the optimized network would remain consistent regardless of the type of object transported and the demand. Consequently, if it was possible to establish a closed loop between cities and incinerators, create a highly efficient network for waste disposal and distribution, and collect raw materials substitutions and reuse of ash for cement production, this would represent a significant advancement in the field. The six optimized scenarios have been spread into 18 Excel worksheets. To facilitate the calculation process, each optimization has been divided into three parts, of which, everyone was allocated in a separate sheet, making it possible to simplify the solver. In the subsequent chapter, the results will be presented and illustrated by maps, which have been generated after the optimization process.

5 Results

This chapter will describe the results from the optimization of both transport systems: waste from cities to WtE plants, and ash from WtE plants to cities, by including 36 cities and 14 sites of WtE plants. The optimal connection between the objectives will be displayed through nine maps, three per optimization. The results after optimizing the network of MSW transport show overuse of the incinerators in only one case. This indicates that in only one of the optimizations, two incinerators were not included in the optimized network (expressed in the table in Fig. 25 by a value of 0). The table below represents the results of the first three optimizations: waste from cities to incinerators. The table illustrates that the production of waste, if transported with an optimized network, will not fill the entire capacity of each incinerator. However, it is important to note that 66% of the population has been excluded from the optimization process.

In the process of optimizing the transportation of ash, a higher number of incinerators were excluded from the network due to the low demand for ash, which was addressed by a few of the waste-to-energy (WtE) facilities. In the next paragraphs, the results will be shown with maps and analyzed.

	2024	2024	2050(1)	2050(2)
Incinerators 2050	**Capacity waste**	After optimization		
AEB(AEC/HRC Amsterdam)	585200	585200	117480	585200
Attero Moerdijk (AEC)	418000	316723.762	974	418000
ARN B.V.	300000	300000	55385	300000
Attero Noord B.V. GAVI Wijster	334400	52883.765	10342	65754.8604
AVR Afvalverwerking B.V. (Rozemburg)	467550	208789.308	8793	303665.538
AVR-Waste (Duiven)	394000	394000	0	394000
EEW Delfzijl B.V.	282150	85704.762	16760	102641
HVCafvalcentrale, Alkmaar	675000	336509.853	28831	467148.823
HVCafvalcentrale, Dordrecht	20000	20000	0	20000
HVCafvalcentrale, Dordrecht	280000	280000	190508	280000
PreZero ReEnergy	121638	36764	7190	77830.0135
REC Harlingen	210000	43243.552	8457	56114.6474
SNB Moerdijk	33000	33000	33000	33000
Twence Afval en energie	377036	288596.09	43796	352951.224

Figure 25: Capacity of Incinerators and their use after optimization

5.1 Optimization of three scenarios

5.1.1 Optimization 1 - 2024

The first optimization regards the current situation in 2024. Capacities of WtE plants are expressed in the first column of the table in Fig. 25, and the production of waste included in the analysis is the current one: 473 kg/cap in 2024. In the first map (Fig. 26) it is represented the connection between the cities (red circles) and the incinerators (green rumbles). As illustrated in the table below, in 2024, the total capacity of all incinerators is not fully utilized. However, none of the incinerators have been deemed unnecessary within the network.

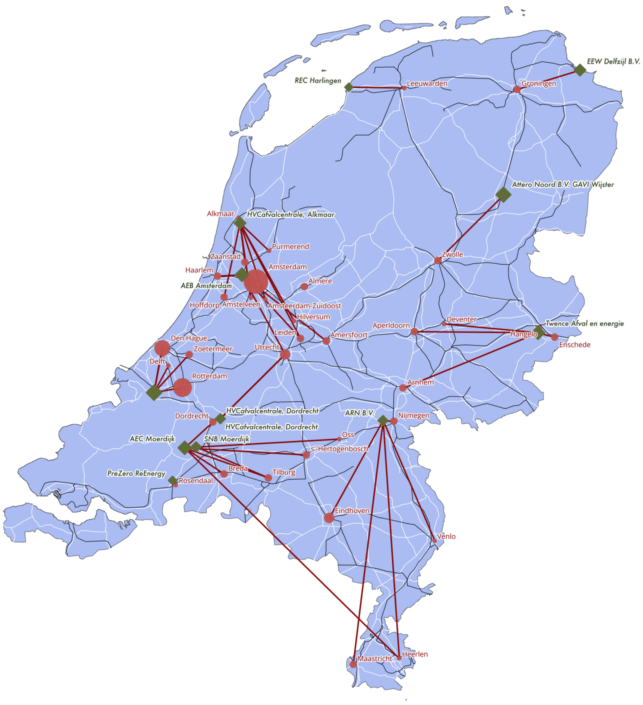


Figure 26: Map 1: optimization transport waste from cities to WtE (2024)

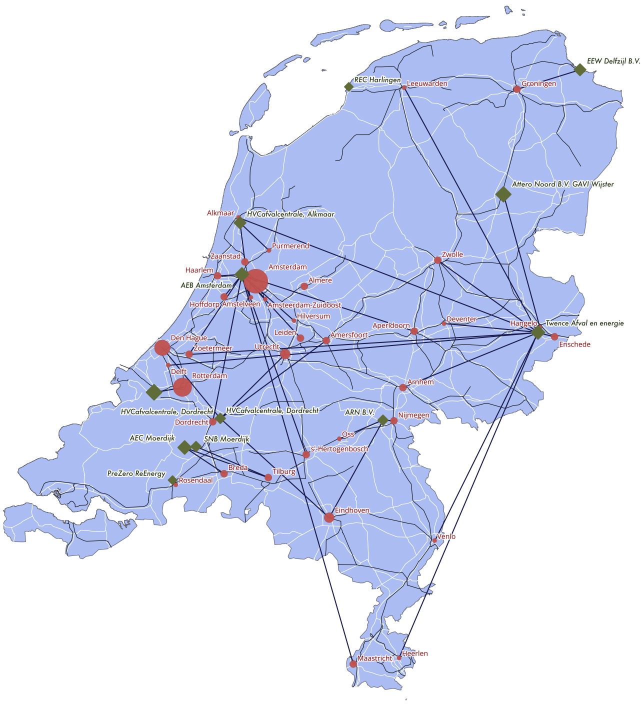


Figure 27: Map 2: optimization transport ash from WtE to cities(2024)

Subsequently, the results obtained from the initial optimization were employed to inform the second iteration, which pertained to the transportation of ash from incinerators to urban centers. Consequently, a proportion of the residual materials were returned to the cities from which the MSW originated, as visible in Fig. 27. In such instances, it can be posited that the objective of establishing a circular system has been achieved. However, the other cases show that the destinations are not compatible, failing the proposal of closing the loop.

5.1.2 Optimization 2 - 2050 - Scenario 1

The second scenario, previously described in Fig. 4.3, is characterized by positive attributes regarding policies and future targets. This scenario represents a complete success of the Dutch goals for 2050, in which waste production is decreased drastically. The waste produced is equal to 375 kg/cap, while the recycling rates are equivalent to 75% of the total production. One consequence of this is the significant reduction in ash production, which makes it more challenging to develop an independent system. However, from the perspective of the Green Deal and landfill and incineration taxes, this could have a positive impact.

The network is easier to analyze due to the low production of waste and ash, which simplifies the connections. However, two WtE plants in the first result and several in the second have not been included due to the low demand. Indeed, some of the cities are not connected to any plant, and vice-versa. The maps in Fig. 28 illustrate the differences between the first and second optimizations, as the different destinations of the two objectives, represented in the second map of Fig. 29.

Figure 28: Map 3: optimization transport waste from cities to WtE (2050)

Figure 29: Map 4: optimization transport ash from WtE to cities(2050)

In conclusion, this calculation demonstrates that the Netherlands' aim to become circular within 2050 is realistic, and the more the production of waste decreases, the easier will be to reach the achieved targets. It can be observed, furthermore, that a consequence of attaining a high level of recycling may be the eventual closure of some waste-to-energy plants.

5.1.3 Optimization 3 - 2050 - scenario 2

To encompass the full range of potential outcomes, the third scenario (2050 number 2) assumes the exact opposite of the previous one. In this scenario, it has been accounted that the policies will not achieve the desired outcomes, and the population will increase due to immigration and longevity [39] by 2050. Consequently, the figures under consideration are significantly higher than those observed in previous cases. While waste production remained stable at 473 kg per capita as of 2024, it is now multiplied by a higher population of 19 million individuals. Consequently, the production of waste, and the residues from incineration, are higher. Nevertheless, both energy and cement demands increase, rendering the utilization of ash for cement production and the incineration of waste a viable solution.

Figure 30: Map 5: optimization transport waste from cities to WtE (2050)(2)

Figure 31: Map 6: optimization transport ash from WtE to cities(2050)(2)

The maps show how the optimization process was designed to identify the optimal connection between cities and plants, like in Fig. 30 and Fig. 31. This resulted in the creation of a complex network. However, it is important to acknowledge that this last network was developed in the context of high demand for transportation due to the high rates of production and demand. The table in Fig. 32 presents the results of ash transport optimization, illustrating the different capacities between incinerators before and after the optimization process. The columns on the right, labeled with orange, represent the ash produced by taking 20% of the total incineration capacity of the plants. While, on the left, the columns labeled blue, represent the ash used to answer the demand in the second part of the optimization. This table elucidates which incinerators have the most strategic locations and capacity, considering both scenarios of higher or lower production of waste, and cement demand.

The incinerators represented in GIS have been selected based on their capacity and connectivity to cities. This approach allows for the identification of factors influencing the operational status of incinerators, such as the higher capacity of ARN BV and HVC Dordrecht, which have consistently remained active.

	Ash brought to the cities to answer the demand after optimization					
	Ash produced in each incinerator base on capacity of incinerations					
Incinerators 2050	2024	2050(2)	2050(1)	2024	2050(1)	2050(2)
AEB(AEC/HRC Amsterdam	110136	23496	117040	117040	23496	117040
Attero Moerdijk (AEC)	14021	195	82649	63345	195	83600
ARN B.V.	19757	11077	40710	60000	11077	60000
Attero Noord B.V. GAVI Wij	4537	2068	13151	10577	2068	13151
AVR Afvalverwerking B.V. (	33080	1759	0	41758	1759	60733
AVR-Waste (Duiven)	0	0	7155	78800	0	78800
EEW Delfzijl B.V.	10173	3352	0	17141	3352	20528
HVCafvalcentrale, Alkmaar	12174	5766	35393	67302	5766	93430
HVCafvalcentrale, Dordrech	0	0	0	4000	0	4000
HVCafvalcentrale, Dordrech	56000	38102	41219	56000	38102	56000
PreZero ReEnergy	4364	1438	6140	7353	1438	15566
REC Harlingen	0	1691	6942	8649	1691	11223
SNB Moerdijk	6600	6600	6600	6600	6600	6600
Twence Afval en energie	57719	8759	70590	57719	8759	70590

Figure 32: Results of ash optimization 3 scenarios

A comparison of the two tables that collect the results of the six optimizations, accompanied by a graphic illustration of them, provides an insight into the differing systems that emerge after calculation. The following paragraph highlights the results to elucidate how the system can be enhanced under the three scenarios.

5.2 Analysis of the results

In the following maps of the figures 33, 34 and 35, green lines highlight the cases where the results of the optimizations are equivalent for both the directions (from cities to WtE and vice-versa). The efficacy of the proposed solution can be determined by examining three key factors: the capacity of the incinerators, the quantity of waste produced by the cities, and the demand for cement from the ladders. If these variables are within an optimal range for the ash generated, the loop can be considered to be fully operational.

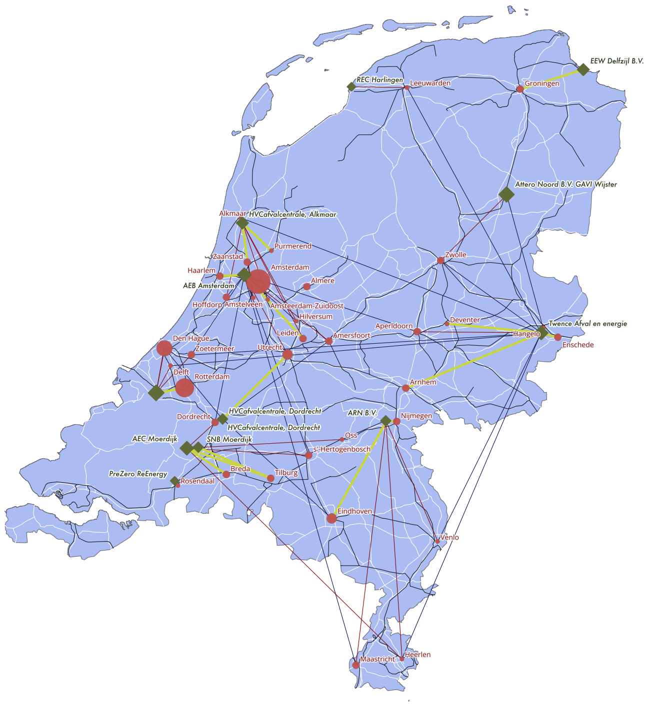


Figure 33: Results of combined supply chain in 2024

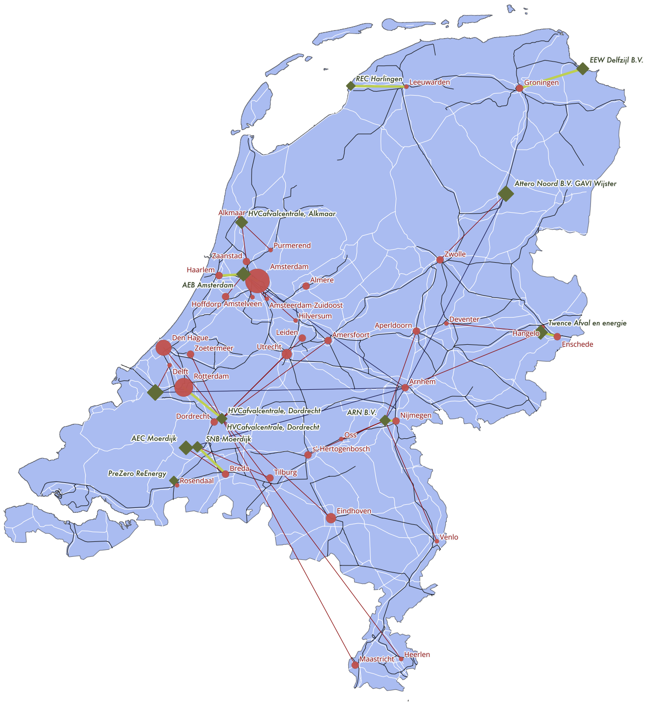


Figure 34: Results of combined supply chain in 2050 (1)

Figure 35: Results of combined supply chain in 2050 (2)

As visible in the maps, it is not the high or low production of waste that properly influences the number of cities that can aim for a circular process regarding waste management and cement production, but the alignment between the capacities and the demand for each objective. It has been observed that cities such as Groningen and Leeuwarden straightly depend on the closest plants, respectively EEW Delfzijl B.V. and Rec Harlingen. While some plants as Attero Noor B.V., ACE Moerjik, and SNB Moerdjik do not appear as often as others, they always have connections with some cities both for the transport of ash and for msw. A third case is that of the large-scale plants, such as AEC Amsterdam, Twence Afval en energie, and HVC Dordrecht. In every scenario, from the lowest to the highest demand or production, these plants were strategic points for many cities, resulting in active and connected involvement with several urban areas simultaneously. Another observation that merits consideration is the role of cities in this network. Some cities, such as Rosentaal or Zwolle, produce and consume relatively little waste and ash due to their relatively limited size and slower rate of growth compared to other larger cities, such as Amsterdam, but also Den Hague, Rotterdam, or Eindhoven. The primary distinction between the waste management logistics of these cities is the proximity of incinerators. In Groningen, Leeuwarden, and Amsterdam, the cities are situated in close proximity to incinerators, whereas in Oss, Maastricht, and Venlo, the cities are located in less optimal locations, being distant from incinerators in all directions.

The subsequent chapter will present a synthesis of the findings from the optimization study, offering a definitive resolution to the research questions initially posed.

6 Conclusion

This chapter presents a synthesis of the preceding material, whereby the research question is addressed and a conclusion is drawn.

6.1 How will the Waste Management be improved in 2050?

The initial section of the thesis sought to address the initial sub-question by examining the existing literature on waste management in Europe and the Netherlands. This was followed by an analysis of waste consumption, cement demand, ash production, and the principal subjects of this topic: the 12 incinerators that were subjected to detailed analysis, and all their characteristics. A lucid account of the waste consumption in the Netherlands and the objectives for the next decades have been delineated.

Second, through the chapters 4 and 5, the calculation of the objective has been defined and analyzed, and results have been presented. Therefore the second and third subquestions were able to be answered. The nine maps show an optimization of the transport system, by taking into account quantities of material transported and the capacities of the plants. Furthermore, an explanation of each optimization has been provided in the three subsequent maps, where the cities and incinerators that result as a two-way connectivity have been highlighted. In conclusion, the results of the study that aimed at achieving more efficient dialogue between cities (question 2) have been presented. In order to respond to the third sub-question, it is necessary to refer to the two future scenarios that have been outlined. As with the previous question, the answer to the third is presented in the chapter above. Given that the scenarios used for the calculation included either a successful achievement of the targets or a missed target, it is not possible to provide a definitive answer as to whether the targets will be reached. Nevertheless, it has been demonstrated what the outcomes would be in both case scenarios.

In considering both scenarios, the thesis demonstrates a wide range of potential outcomes, where each solution can be found within this spectrum. Furthermore, the adapted model can be applied to any solution within this range. In conclusion, the aim of this analysis is to demonstrate the potential impact of different policy scenarios on the reuse of ash from incinerators for the production of sustainable cement.

6.2 Answer problem question

Probelm question (2.3): "Considering the Netherlands as one of the most advanced countries in terms of reaching the Green Deal goals, and aiming to be 100% Circular in 2050, how can the waste-to-energy system and the use of ash for sustainable cement be improved to fit the proposals?".

The purpose of reporting the main problem question is to remind the reader of the initial aim of the thesis and how the process answers it. This will be elucidated in the subsequent paragraph.

To reach a conclusion that can answer the initial question, the thesis aimed to answer first the three subquestions, along with the process of studying the literature, collecting data, proposing hypotethical future scenarios, and calculating the optimized network.

The thesis has been inspired and guided by the sources "The Urban-Industrial metabolism: contribution of waste recycling to the circular economy objectives within the construction sector" and "Optimal supply chain networks for waste materials used in alkali-activated concrete fostering circular economy" and their author Anastasija Komkova and Guillaume Habert. The research aimed to find solutions for the circularization of waste management by using incineration residues from municipal solid waste, swage sludges and biomass incineration in the Netherlands. To approach this closing loop, which is illustrated in the Fig. 36, the first step is to improve the urban industrial metabolism, by optimizing the transport network.

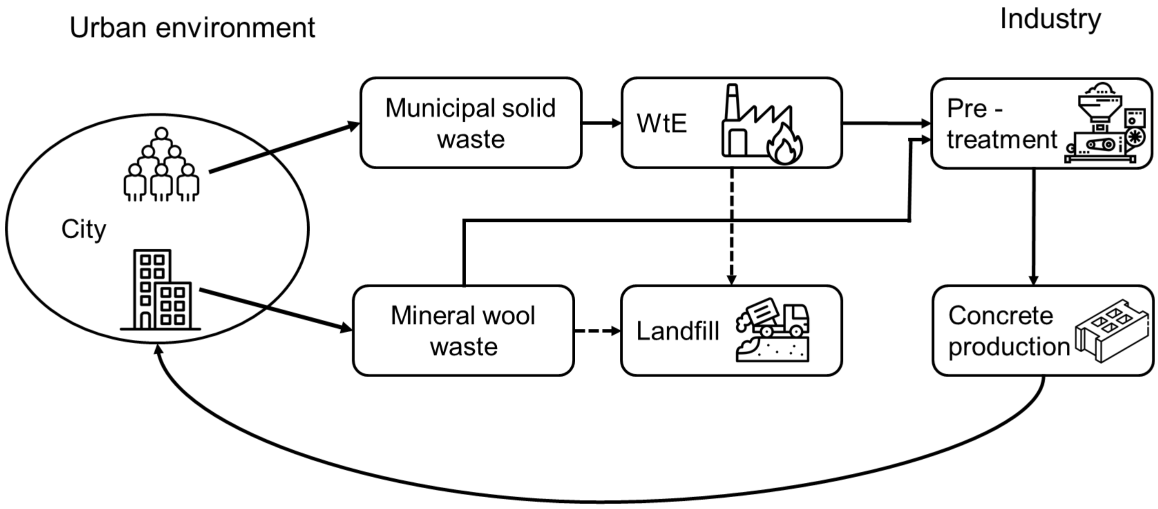


Figure 36: Proposed waste recycling within the Urban-Industrial metabolism framework [13].

The thesis demonstrates that the optimisation of the network in the present can diverge significantly from that of a hypothetical 2050 scenario, yet also show important similarities. The pivotal factor influencing the outcomes is the efficacy of the policies in question. The world is currently experiencing a delicate transitional period, during which every action and proposal must be carefully considered due to the narrow margin for error. In light of this, the thesis aims to provide the most strategic solution for potential future scenarios in the waste management sector in the Netherlands. It is important to note that by presenting multiple scenarios, it is not possible to provide a definitive answer to how the future will unfold. Moreover, as previously stated, the lack of data and the decision to focus on only a third of the actual population made it challenging to provide realistic results. Nevertheless, the objective is to provide an illustrative and inspirational example for future studies. In conclusion, the answer to the main problem question is strightly connected to success of the European goals of following the Green Deal proposals, and the aim of the Netherlands to become a circular economy by 2050. With the defended technology it will be possible to integrate the ash residues from incineration into the loop, closing the cycle and making the urban-industrial symbiosis a solution for this aim. Nevertheless, the figures presented in the current scenario may undergo significant alterations. Furthermore, the WtE plants that are currently operational in the Netherlands may alter or cease their operational status. Despite this, predictive models have been developed to assist in the identification of viable solutions for countries such as the Netherlands, which are striving to achieve a circular economy through the implementation of various types of urban industrial symbiosis systems, including the utilisation of waste-to-energy residues for the construction sector.

7 Reflections

7.1 Limitations: data collection

During the research, several problems were encountered. Firstly, the difficulty of finding data was encountered. Since the topic is not as widely discussed as was initially anticipated, the relevant data useful for the creation of scenarios and calculation of optimised networks was challenging to locate. Indeed, the majority of data regarding waste management is updated to 2021 or 2022, and it was assumed that the situations had not changed. With regard to cement production, the data available tend to focus on fluctuations in prices and markets, with less attention paid to use or production. Indeed, forecasts indicate that this is an area that is still developing in many countries in Europe. Consequently, it was challenging to identify papers on this topic.

Another data collection exercise that encountered difficulties was the collection of data regarding each incinerator. As previously stated in the thesis, data regarding waste processing, incineration, and the production of energy, heat, and ash were not always available. It is important to note that the source data used as the basis for this research was published in 2012. Although the principal incinerators are characterised by being large companies with an interest in growth, it is in their interest to demonstrate in their annual reports, for example, the quality of their work. Consequently, this figure allowed me to gain an insight into the numbers in some of the plants.

7.2 Future Research

With regard to the results, the objective of the optimisation model was to identify the optimal transportation network, taking into account the capacity of plants and the demand of cities. However, to achieve more accurate results, it would be beneficial to adapt the model to circular targets. This would involve instructing the solver to not only identify the most efficient trajectory, but also to consider returning to the initial point when feasible. This approach is illustrated by the green lines in the chapter5, which displays more promising outcomes. In conclusion, the results could have been more promising with more data, more time, and an adaptation to circular targets.

Nevertheless, the initial rationale for focusing on the Netherlands is its exemplary position in waste management in Europe. Consequently, the availability of information on this topic is relatively more extensive in the Netherlands than in other countries with less up-to-date data. It would be beneficial for future researchers to extend their investigation to other European countries, to make an archive with data regarding this topic more easily accessible. This, thus, will provide a more comprehensive understanding of the current status and potential avenues for improvement in waste management across the continent.

8 Acknowledgements

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Appendix

Additional Data:

- tables of Xcel imported on GIS
- Matrics developed in GIS to find the best roads

Technical Details:

- energy, consumption, production data
- math calculations to determine the relation between cities and plants
- math calculations to determine the 2 possible scenarios

Supporting Documents:

pdf, files, tables from plants / companies websites

Supplementary Material: