Food Waste through the Food-Water-Energy Nexus Lenses

A Case Study of Amsterdam

An Industrial Ecology Approach

MASTER THESIS

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An Industrial Ecology Approach

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Abstract

Food waste is a global issue that causes various but significant global impacts, wasting millions of hectares of arable land, 0.75 to 1.25 trillion of cubic meter of water per year, and about 1.5% of the global energy production. In developed nations, food waste occurs mainly at the retail and consumer stage. By 2050, 80% of the global food consumption will take place within cities. Cities are also a key nexus of energy, water, and food flows. Amsterdam offers an interesting case study as the city does not have any comprehensive strategy to tackle the food waste produced within its boundaries. Yet, the city has shown ambitions in transforming itself into a sustainable metropolis with strong renewable energy and circular strategies. This study uses the Food-Energy-Water (FEW) Nexus approach, particularly suited to understand the interactions and interconnections between Amsterdam's food flows and the energy and water systems.

This study performs a Material Flow Analysis to quantify the different food waste (FW) flows and their origins. It finds that households are the main producers of food waste compared to FW-producing businesses in Amsterdam. Bread, dairy, vegetables, and fruits are the largest avoidable FW, while vegetable peels, fruits peels, coffee grounds, and potatoes peels constitute the bulk of unavoidable food waste. It then quantifies the embedded energy and water present within these food flows. Using the latest developments in the field of bio-based economy regarding food waste valorization, it provides an inventory of the potential technologies available to valorize Amsterdam's FW. The study then quantifies the energy and water inputs of 12 of these food waste-valorizing technologies. This step confirms the large knowledge gap regarding the water and energy intensities of the latest bio-based technologies. The type and amount of recovered resources through these technologies are also quantified. In addition, this study provides a review of the current social and commercial initiatives based in Amsterdam tackling this issue of food waste. It offers a six-category qualitative framework to assess their food waste rescue potential. Then, a new food waste management and valorization framework is proposed, based on the *Value Pyramid* model from the bio-based economy, the Food Waste Management Hierarchy framework, and the FEW nexus insights developed in this study. This new framework enables to outline strategies for both Amsterdam's avoidable and unavoidable food waste flows. It suggests anaerobic digestion, Black Soldier Fly bioconversion, and composting as potential FEW-efficient solutions for Amsterdam's unavoidable FW. Last, Amsterdam's FW stakeholders are analyzed through their importance, interests, and potential roles in a future FW scheme. It suggests that the municipality and AEB, Amsterdam's Waste-to-Energy plant should be at the center of a future FW valorization scheme.

Overall, this study combines the FEW nexus perspective and the bio-based economy approach to identify the best options to manage and valorize Amsterdam's food waste.

Keywords: urban food system; food waste; FEW nexus; bio-based economy; MFA; industrial ecology

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List of Abbreviations

AFW: Avoidable Food Waste

IE: Industrial Ecology

FEW: Food-Energy-Water

FSC: Food Supply Chain

FW: Food Waste

FWMH: Food Waste Management Hierarchy

LCA: Life-Cycle Assessment

MFA: Material Flow Analysis

UFS: Urban Food System

UFW: Unavoidable Food Waste

UM: Urban Metabolism

WtE: Waste-to-Energy

1. Introduction

Food waste is a global issue worldwide which has dire consequences both for the human population and the environment. It is estimated that about 30% to 50% of the total food production is lost throughout the global food supply chain. This is equivalent to wasting between 1.5 and 2 global hectares of arable land worldwide, 0.75-1.25 trillion cubic meters of water per year, and between 1 and 1.5% of the yearly global energy production (Fox, 2013). At the same time, about 815 million people worldwide suffer from undernutrition (Horton et al., 2016).

In developed countries, food waste overwhelmingly occurs at the retail and consumer stage (Aschemann-Witzel, 2016). Food waste is driven by multiple trends such as economic growth, population growth, and urbanization (Thyberg & Tonjes, 2016).

Furthermore, urban dwellers are expected to represent 66% of the 9.5-billion human population by 2050 (UN, 2017). As an increasing share of the global population live in urban centers, people are increasingly disconnected with their food sources and food waste is being more and more concentrated in cities (Thyberg & Tonjes, 2016; Seto et al., 2017). As cities grow worldwide, both in economic and demographic terms, it is expected that 80% of the global food consumption will take place in cities by 2050 (EMF, 2018).

Urban spaces are therefore a key nexus of food waste but also energy, water, and other waste streams. From a systems perspective, (urban) food waste (FW) is part of the Urban Food System (UFS). In turn, the concept of UFS stems from the Urban Metabolism (UM) approach.

UFSs encompass the different ways of food provisioning in urban spaces, i.e. where food is produced, processed distributed, and sold (Wiskerke, 2015). The UFS is part of the greater agri-food system (Wiskerke, 2015). More broadly, the academic field of UM attempts to quantify the current and future energy and material needs of cities (Musango et al., 2017). FW is thus an important output within the metabolism of cities that ought to be quantified and analyzed.

The field of Industrial Ecology (IE), which aims to analyze the energy and material throughput of society, is particularly suited for this task (Ehrenfeld, 1997; Ehrenfeld, 2004). In the last three decades, the field of IE has developed multiple tools, such as Material Flow Analysis (MFA), to quantify material and energy flows in industrial systems, aiming to develop solutions grounded in natural, engineering, and social sciences to increase its circularity. These tools have increasingly been used in UM studies.

Although food, alongside material, water, and energy, is an important input in the urban system as it is one of the main contributors to global warming, few IE studies have addressed this topic (Goldstein et al. 2017). Nevertheless, a rise in consumer awareness and in local government's sustainability policies have increasingly put food back at the center of urban development, whether from a food security or waste management perspective (Zeuw &

Dubelling, 2012). UFSs are therefore gaining momentum, both in policy and urban-research, which begs the question on how IE can contribute to this new research area.

UFS studies are increasingly intertwined with the energy, water, and nutrient flows present in cities. Food, energy, and water represent the main building blocks for human existence (Heard et al., 2017). As a result, the demand for food, water, energy is increasing, and urban centers represent a focal point of these complex interconnections. UM has been a promising approach in uncovering the different dynamics, interrelations, and interdependencies within this Food-Energy-Water (FEW) nexus in cities (Heard et al., 2017). Thus, a systemic or nexus analysis of the different systems (i.e., water, energy) interacting with FW is a critical endeavor, particularly suited for the field of IE. Additionally, FW represents an important stream of organic resources, which places it under the umbrella of the so-called bio-based economy.

The bio-based economy aimed to transition the economic system from a fossil-based to a biomass-based system through the research and development of biotechnologies and bio-industrial processes. It aims to replace fossil fuels in the production of chemicals, materials, and energy (Staffas et al., 2013).

The bio-based economy stirred early on controversies due to its emphasis on the use of biomass to produce non-food related products such as biofuels and other bio-chemical products (Mannan et al. 2018). Due to a lack of a nexus perspective, the rise of a bio-based energy system could consequently lead to an increased pressure on the food system (i.e., land and resource competitions). For example, the first generation of biofuels made from corn crops competed with food production.

Nonetheless, the bio-based economy has turned increasingly toward the use of alternative resources as illustrated by second-generation biofuels produced from waste products such as cooked oils (or even third generation using algae). The concept and framing of the bio-based economy (and by extension the circular economy) becomes therefore particularly suited to assess resource recovery options from FW. This study's value resides therefore on the use of the Food-Energy-Water nexus system perspective to generate insights for an urban system in the best FW recovery options developed within the bio-based economy.

In this thesis, the municipality of Amsterdam was selected as a case study to perform an analysis of the FW flows present within the city's boundaries. Amsterdam is the capital of the Netherlands, and is home to 833, 420 inhabitants. Over the last decade, Amsterdam has been pro-active in developing a circular roadmap for the future development of the city and has set ambitious targets regarding renewable energy production (20% increase), energy use reduction (20% reduction by 2020 for each resident), and CO2 reduction (40% decrease by 2040, relative to 1990 levels) (Hoek et al. 2015; Gemeente Amsterdam, 2015).

However, the city of Amsterdam does not currently have a comprehensive FW management and valorization program, as most household residual waste is incinerated in a waste-to-energy plant. By and large, the municipality of Amsterdam has no recovery strategy for any organic waste (GFT) at the household level (Gemeente Amsterdam, 2015).

Beside households, companies ranging from supermarket to food processing facilities, present within the city's boundaries are important producers of FW.

There are few initiatives, mainly grassroot, citizen-based organizations, that aim to rescue FW, that is, collect food products from supermarkets and restaurants that would otherwise be thrown away. Other commercial initiatives developed online platforms (e.g., Too Good to Go) on which baskets of food that would be soon discarded are sold for a discounted price. This is made possible due to partnership agreements with restaurants, bakeries, and supermarkets.

Amsterdam is an interesting case study as the city is very concerned about its waste management strategies and aims to integrate organic waste within its waste management programs (Gemeente Amsterdam, 2015). Furthermore, there is a sizeable amount of data due to the comprehensive work performed by the CREM and the REPAIR teams, which both focus on FW within the Amsterdam region.

This case study is analyzed both using a traditional tool of IE, namely a Material Flow Analysis (MFA), and the food-energy-water nexus (FEW nexus) system perspective. The bio-based economy approach to FW recovery is also used in this study to assess recovery options, by using the *Value Pyramid* and the Food Waste Management Hierarchy as guiding frameworks (Welink, 2015; Eickhout, 2012; Papargyropoulou et al., 2014). Amsterdam FW-related stakeholders are analyzed due to their importance in the establishment of a FW recovery program.

Last, from a FEW-perspective, the performance in terms of water and energy use of the different recovery options are key to understand the different valorization options available (Kibler et al., 2018).

The main research question of this thesis is: *To what extent can the FEW-nexus perspective, combined with the bio-based economy approach, help identify the best options to manage and valorize urban food waste streams?*

This research question is further broken down into six sub-questions.

- SQ1: What are the main intersections between the urban FW flows and the FEW nexus?
- SQ2: What are the main food waste flows of Amsterdam?
- SQ3: How much embedded energy and water are present in Amsterdam's FW streams?
- SQ4: What are the initiatives and technologies available to valorize urban food waste products?
- SQ5: What are the best options to recover FW from a FEW nexus perspective?
- SQ6: What advantages and limitations have been encountered by applying the FEW nexus approach to the urban food waste issue?

First, a thorough literature review is performed to identify the main research findings, trends, and gaps in FW studies, FEW-nexus studies, and studies focusing on bio-based applications for FW valorization. Then, the methodology used during this study is described in detail.

Subsequently, the first chapter presents and describes the position of the case study of Amsterdam's FW within the FEW nexus approach, describing the main systems' interconnections, the main stakeholders, and the main results to quantify.

The second chapter focuses on the results of the MFA that quantified FW flows within Amsterdam, both stemming from households and from FW-producing businesses.

The third chapter presents the energy and water embedded in Amsterdam's FW flows, and quantifies the resulting loss of energy and water related to the FW flows.

An inventory of the technologies and food rescue initiatives implemented in Amsterdam is presented in the fourth chapter. The different valorization strategies for Amsterdam's FW streams are subsequently presented.

The fifth chapter is concerned with the energy and water inputs of a variety of valorization technologies falling under the umbrella of the valorization strategies presented previously. These technologies' outputs, stemming from the valorization of FW, are also quantified.

The sixth chapter explores the *Value Pyramid* (VP) model from the bio-based economy and the *Food Waste Management Hierarchy* (FWMH) framework designed by Papargyropoulou et al. (2014). A new FW management and valorization framework is suggested, that is grounded in both mentioned frameworks and by integrating a FEW nexus perspective into FW valorization strategies. This framework is then applied to Amsterdam case study.

The seventh chapter analyzes the different key stakeholders' importance, interests, and roles in the implementation of a future FW management and valorization scheme in Amsterdam.

Finally, the eighth chapter discusses all the results developed throughout this study, reviewing the limitations of this work, providing a critic of the FEW nexus system perspective for FW studies, and presenting future research pathways. It also makes recommendations to the municipality of Amsterdam for the implementation of a future FW valorization scheme, and for FW and FEW nexus research practitioners.

2. Literature Review

2.1. Food Waste studies

There is a lack of a universal definition for FW, as understood from a review of several articles (Xue et al., 2017, Kibler et al., 2018, Parfitt et al., 2016, Quested and Johnson, 2009). For example, Parfitt et al. (2016) recommended the definition developed by the Food and Agriculture Organization (FAO) in 1981. The organization defined FW as any human-intended edible food item, that prematurely exits the food supply chain (FSC) because it was discarded, lost, or degraded through handling or by pest (FAO, 1981; Parfitt 2016). Although this definition is rather exhaustive, it lacks another layer of characterization that has been emerging recently in FW studies. FW can indeed be further defined into two main categories: avoidable FW and unavoidable FW (Berreta et al. 2013; Corrado et al. 2017; CREM, 2017).

Unavoidable food waste represents all the commonly inedible portions of food products that are discarded, such as peels, cartilages, or shells. On the other hand, avoidable food waste constitutes the main edible portions of food products that are thrown away. The difference between unavoidable and avoidable FW has a certain level of subjectivity, depending on a variety of factors such as cultural and economic behaviors (Corrad et al., 2017).

Certain studies added a third category of "possibly avoidable FW", but for simplicity, the FW definition adopted in this thesis will only consider unavoidable and avoidable FW (Berreta, 2013; Quested & Johnson, 2009). From a systems perspective, total FW is therefore composed of unavoidable (UFW) and avoidable food waste(AFW) (Corrado et al. 20170).

FW occurs along the whole supply chain, but as mentioned previously, in developed nations the losses tend to occur at the retail and consumer stage (Aschemann-Witzel, 2016). As stated in the introduction, the main goal of this study is to develop insights into the FW recovery strategies for the city of Amsterdam. Thus, this literature review gives a special focus on FW treatment and recovery practices rather than focusing heavily on FW prevention. Yet, it must be noted that there is an extensive literature of FW prevention at the household and food manufacturing level (Schane et al., 2018; Pearson et al. 2013; Quested et al, 2013; Morone et al., 2019) and FW prevention is a crucial aspect when tackling FW issues, as it will be shown later on in this study. A brief overview on the literature on FW prevention is presented in the next few paragraphs. Afterwards, the rest of the review focuses on FW treatment.

2.2. Food Waste Prevention

Schane et al. (2018) reviewed the main factors leading to FW and impeding FW reduction strategies at the household level. The study highlighted the fact that as the FW prevention literature was growing, the FW was increasingly considered to be caused by a complex arrangement of factors, with none that could be particularly single out. They found that guilt was an important factor for the avoidance of FW, though guilt was usually linked to financial concerns rather than social and environmental concerns. FW reduction strategies were impeded not only due to the lack of awareness of the social and environmental costs of FW, but also in the lack of confidence in one's ability to reduce household waste due to increasingly complex routine schedules (Shane et al., 2018).

Lee (2017) analyzed FW occurrence by looking at the influence of different types of food retailers' format. They found that out of a range of different retail formats (e.g., hypermarket, supermarket, traditional market), hypermarket led the largest amounts of AFW for the households purchasing their food there. More importantly, the frequency of food purchasing and the distance to the retail store (regardless of the retail format) was key in the amount of AFW produced. The more frequent and the shortest distance led to significantly less AFW at the household-level compared to infrequent purchases (Lee, 2017).

Hooge et al. (2017) analyzed how the cosmetic appearance of products influences food wastage at the grocery store and at the household level. They found that sub-optimal products were considered differently at the supermarkets and within households, which may have implications for FW policy development and awareness campaigns. Furthermore, they notably found that consumers were willing to purchase most sub-optimal produces if a discount was offered (Hooge et al., 2017). An interesting aspect regarding consumers' consideration of sub-optimal product was the nuances found by the study in terms of *"sub-optimality types*". For example, shape did not seem to be of great important for the consumer while color may increase the need for greater incentives to purchase the products with this type of suboptimality (Hooge et al., 2017). Last, consumers with more regular cooking practices are more attuned to buy suboptimal products.

FW prevention studies also cover packaging (Poyatos-Racionero et al., 2018), shelf-life management to reduce FW in the agri-food supply chain (Gokarn & Kuthambalayan, 2017), FW prevention in canteens (Boschini et al., 2018), and various aspects of consumer behavior change to reduce FW (Revilla & Salet, 2018; Morone et al., 2016).

2.3. Food Waste Treatment

As most developed nations are heavily urbanized, the FW is therefore treated in the local urban waste management systems. Furthermore, since FW contributes significantly to urban greenhouse gases emissions and other toxic pollutants, such as dioxin (e.g., during wet FW incineration), FW studies focus considerably on investigating FW processing technologies (Goldstein et al., 2017; Seto & Ramankutty, 2016; Paritosh et al., 2017).

In a study on FW reuse and recycling in Taipei city, Tseng and Chiueh (2015) combined a network metabolism approach and a Life-Cycle Assessment to map out the city's FW flows and determine which FW conversion processes would be best for the city. The study found that composting after cooking the FW at a high temperature was the best conversion technology to recover energy and materials from the FW flows while minimizing environmental impacts to the city. On the other hand, converting FW into bio-ethanol had the most environmental impacts.

In another study, Paritosh et al., (2017), found that anaerobic digestion was one of the most environmental-friendly process to treat FW, recovering energy from the extracted biogas, and recycling nutrients. Overall, energy production from burning biogas (mainly biomethane) extracted from FW has been widely acknowledged in the literature.

As FW production is expected to rise, local carbon-neutral energy production from FW, though not a panacea, can partly offset the energy input lost when the food products left the supply chain unconsumed (Adhikari et al., 2006; Curry & Pillay, 2012).

Consequently, FW conversion into energy ought not to be the first option when it comes to dealing with FW. For example, Papargyropoulou et al. (2014) developed a FW management hierarchy (FWMH) framework ordering the FW management actions from favorable to less favorable. The best option to avoid FW is too avoid surplus. Reusing FW (with some preparation) to connect it back to the population suffering from food security is the second most favorable option (Papargyropoulou et al., 2014). Recycling food through animal feed conversion and composting is the third best option, while energy and nutrient recovery, alike the processes mentioned above, is only ranked the fourth option (Papargyropoulou et al., 2014). Landfilling is the least favorable option. It can be noted that this framework echoes the framework developed on the Circular Economy (CE) by the Ellen McArthur Foundation (EMF, 2010).

The main drawback from this framework remains the absence of innovative valorization options for FW, other than energy and composting. This framework will be further addressed in Chapter 6.

In this thesis, FW is considered as resource that can be recovered at different stages of its life-cycle in order to extract a maximum amount of value and limit its environmental impacts. This concept of FW as a resource falls under the umbrella of a larger concept, namely the bio-based economy, which primarily focuses is the valorization of bio-based products in the current economic system. This concept represents an important aspect of this thesis and therefore ought to be further described.

2.4. Bio-based Economy and Food Waste Treatment

The concept of the bio-based economy refers to the use of resource of biological origins and the conversion of renewable carbon sources into a wide variety of products ranging from animal feed, food products for human consumption, (bio-based) chemicals, (bio)polymers, biofuels, and other form of bio-energies (Maina et al., 2017). As rightly pointed out by Maina et al. (2017), the circular economy is complementary of the bio-based economy, as the former is based on the re-use and recycling of materials, with the overarching goal to preserve materials to their highest functional value.

In his report on the valorization of FW from processing industries in North-Holland, Welink (2015) highlights a useful pyramidal hierarchy, named the *Value Pyramid,* adopted by the bio-based economy concerning the economic value of biomass (Eickhout, 2012). Pharmaceutical products are located at the top of the value generated by biomass, followed by fragrances, and natural flavors. Fruits and vegetables for human consumption remains high in the biomass value hierarchy, though below pharmaceutical and cosmetic products. Welink emphasized that each group of substances present in the value pyramid can use FW streams as main feedstocks. Functional molecule, fermentation derivatives, and fibers are also valuable products for different chemical industries (Welink, 2015). Fuel is located at the lowest level of the biomass (economic) value hierarchy.

This framework does not however put forward the need for FW prevention, and controversially does not put food for human on top of their economic value pyramid (Eickhout, 2012). A further analysis of this framework will be developed in Chapter 6.

Several studies have focused on transforming FW into valuable products. Mirabella et al. (2014) performed an in-depth review of the currently available technologies.

The study highlighted the core steps in FW recovery. Identifying, quantification and characterizing FW residues ought to be the first step of such a process. Then, classifying FW sources and added-value ingredients help scope down the different recovery phases, and finally browse through current and emerging technologies capable of processing them (Mirabella et al., 2014). This approach is particularly similar to the one used in this thesis report.

Their review focused first on vegetable and fruits FW processing, exploring the potential of several specific products. For example, taking the case of apple industrial processing, apple pomace (a by-product from making apple juice) may be used for fuel purpose, extract pectin (natural thickening agent) or used as cattle feed. Furthermore, apple skin can be transformed into highly nutritional natural food additive due its high concentration of phenolic compounds and antioxidants.

In addition to apple, Mirabella et al. (2014) reviewed FW processing technologies for berries, tomatoes, citrus, exotic fruits, potatoes, dairy products and meat. Overall, their paper builds a strong basis for eco-innovations related to FW. The REPAIR team also provided a short compilation of eco-innovation solutions to reuse FW, with the particularity of considering the geographical context of their different case studies. For example, they presented the case of vegetable and fruit peels turned into “vegetal leather” (REPAIR, 2018).

A recurring issue for reprocessing FW remains that treating a single stream of waste is often highly costly and the economic feasibility is not proven for all recovery technologies (Mirabella et al., 2014; Maina et al., 2017). Maina's et al. (2017) suggest the idea of creating bio-refineries able to process diversified streams of specific types of waste (e.g., flour, wineless) to offer a whole range of products, and thus catering to different market demands. By developing flexible biorefineries, it will increase their economic viability and develop key infrastructures for the circular economy.

In the literature, there is a recurring tension between the need to prevent FW and its valorization. To breach the gap, Morone et al. (2019) suggest two guiding principles to tackle issue of FW. The first one entails the minimization of avoidable waste while the second refers to the maximization of the valorization of unavoidable food waste. Surprisingly, it is one of the first papers to clearly attempt to reconcile FW prevention and valorization. It requires an increase connectivity between the different stakeholders from both side of the solution to FW (Morone et al., 2019).

Although it was seen that FW treatment were analyzed from a broad environmental-stand point (e.g. carbon footprint), the water and energy use of FW treatment remains another important question to be addressed (Kibler et al., 2018). Indeed, FW treatment is also tightly with the larger energy production (e.g., biogas), and food production systems (e.g., nutrients). It appears clear that FW is more than just a waste management issue, and it rather intertwined with other urban systems, such as energy and water. As a result, an interdisciplinary approach, as well as a systemic point of view to identify possible solutions to this growing urban challenge must be sought. The Food-Energy-Water (FEW) nexus perspective may therefore particularly be suited to analyze FW issues.

2.5. Food waste and the FEW Nexus Perspective

FW flows are not isolated but depend on other important flows such as water and energy. The Food-Energy-Water (FEW) nexus is a systemic perspective that has gained momentum during the World Economic Forum in 2011 that focused on food, water, and energy security (Albrecht et al., 2018). The FEW nexus perspective sees the water, food, and energy systems as highly connected and mutually dependent. It was established as a novel way to deal with global challenges such as urbanization, accelerating development, degradation of resources, climate change, and globalization (Hoff, 2011).

The overall aim is to encourage policy coherence across sectors, increase resource productivity, foster a waste-as-resource approach, poverty alleviation, economic development, and capacity building (Hoff, 2011).

In their review, Albrecht et al. (2018) aimed at providing an overview of the FEW nexus perspective application in research. The FEW nexus perspective is characterized by a wide diversity of methodologies, both quantitative and qualitative. FEW-nexus approach studies are often innovative in their methods, influenced by their context, cross-sectoral, and produce implementable results (Albrecht et al., 2018).

For example, Villarroel et al. (2014) applied this approach to the city of London. Using a Multi-Sectoral Systems Analysis (MSA) framework, they first mapped with a MFA the energy, nutrients, and water flows of the city's different sectors, and then identified the synergies and trade-offs arising between the different urban sub-systems (Villarroel et al., 2014). The study then developed scenarios where multiple water technologies were applied to parts of the urban systems and quantified the economic benefits. This systemic approach can be very valuable to UFS studies. There is a variety of FEW-nexus framework that has been developed in an attempt to define the notion and turn it into a practical research tool.

2.6. FEW-Nexus Frameworks

The FEW nexus system perspective has attracted attention of researchers and international organizations; therefore multiple frameworks have been developed to study the nexus.

For example, the FAO developed a general FEW-nexus methodology that relies on an initial qualitative assessment of the local context, and then on a quantitative analysis of the different linkages water-food; water-energy, food-energy…etc. (Flamini et al., 2014).

With the multiplication of FEW-frameworks, several studies have attempted to review the main FEW nexus tools or frameworks available to practitioners (Shannal et al., 2018). Kaddoura et al. (2017) reviewed seven nexus frameworks.

First, the CLEW (climate, land-use, energy, water) framework aims to highlight the synergies and trade-offs with the four different areas when it comes to achieve development goals. The core and most interesting aspect of the CLEW resides in its system thinking approach to understand the dynamism between the different areas (Kaddoura et al., 2017). As explained by Bazilian et al. (2011), the overall goal of the CLEW is to improve decision-making, harmonized policy efficiency, and developed scenarios. The study suggests that the CLEW may breach the different policy silos and be of great importance for the future of developing countries (Bazilian et al., 2011). One of the main difficulties of this framework remains its intensive data requirements.

Second, the *Water, Energy, Food nexus Tool 2.0* originally developed by Daher and Mohtar (2014) is an online tool accessible to the public. It offers to assess different scenarios and quantify rapidly the energy, water, and land-use (for food) requirements for such a scenario and yields an overall sustainability index of the scenario. The scenario also includes economic parameters into it. While its main strength is the ease of use for the public, the intersections between the FEW nexus remain extremely simplified (Kaddoura et al., 2017).

Third, the MuSIASEM Flow Fund model is a nexus framework focus on resource accounting and the analysis of metabolic patterns. Using complex theory system and flow-fund models from bioeconomics, the framework can assess different variables (economic, social, ecological, demographic) while using data with different scales. A major drawback remains that the framework can appear highly complex for non-trained users (Dargin et al., 2019).

Kaddoura et al. (2017) also reviewed the MARKAL/TIMES framework focused on energy model, and the WEAP framework focused on water management tools. Both tools are very useful in their own system (respectively energy and water) but cannot operate as stand-alone framework to study FEW-nexus processes.

Several FEW-nexus frameworks were also spontaneously developed for case studies. For example, Karnib (2017) developed a quantitative framework of the FEW-nexus, that analyzed the three systems as interconnected resources across different sectors, and applied it to a case-study on Lebanon. It yielded interesting insights on the connectedness of the nexus, such as the energy-use-for-water and the water-use-for-energy, which reacted differently following different policy projections.

Unlike regional or national-scale FEW-nexus framework, Hussien et al. (2017) provided a comprehensive framework to assess the FEW-nexus at the household scale. Although it is based on bottom-up data from Iraqi households, the system dynamic model is very comprehensive and yields a very accurate view of the dynamics between the three systems at the household-level. The model was tested with several global scenarios to see how the FEW nexus behaved at the household level. One of the main strengths of Hussien et al.'s integrated model is its replicability to other household contexts.

Last, instead of creating a comprehensive framework, which can often seem inflexible and maladapted to many research contexts, Daher (2017) developed seven guiding questions for any research project interested in integrating the FEW-nexus in its approach. These questions are noteworthy in the context of this study as they are used later on to incorporate an analytical FEW nexus layer in this research process on FW. Table 1 provides a summary of the frameworks mentioned above.

Table 1: FEW-nexus Frameworks	
Name	**Description**
CLEW	System thinking-oriented tool focused on harmonizing development policies by using the FEW nexus system perspective.
Water, Energy, Food nexus Tool 2.0	Simple online platform that computes the most basic connections between the food, water, and energy systems.
MuSIASEM Flow Fund model	Use complex system theory and flow-fund models to offer insights on metabolic patterns within a system.
WEAP	Water-centric model to improve decision-making on water management strategies. This framework may be integrated in a wider FEW nexus framework.
MARKAL/TIMES	Energy-centric model to inform decision-makers on energy strategies through different energy scenario modelization. This framework may be integrated in a wider FEW nexus framework.
Lebanon FEW-nexus Assessment (Karnib, 2017)	A FEW nexus framework developed to study the connectedness of the nexus at a country-level.
Household-level FEW-nexus (Hussien et al., 2017)	A FEW-nexus framework developed for the house-scale, case study in households in Iraq.
7 FEW-nexus Guiding Questions-(Daher et al., 2017).	Seven questions to approach FEW nexus modeling for different types of case studies.

Few Food-Energy-Water nexus frameworks have been developed to assess FW issues. Kibler et al., (2018) created a conceptual framework to understand how FW interacts with the FEW-nexus (Fig. 1).

The framework illustrates how FW affects and is affected by the FEW-nexus. FW is connected upstream in the FSC by water and energy inputs for the different food production stages but also downstream with energy and water use to treat FW (Kibler et al., 2018).

Their work also revealed how little is still known about the amounts of energy and water needed to treat FW and how they varied depending on the possible range of technologies available. Moreover, their findings suggest that no comparison has been made so far between the amounts of water and energy needed for food production and the amounts for FW treatment (Kibler et al., 2018).

Their study highlighted four key questions that ought to be solved regarding FW valorization, notably how much water or energy is used throughout FW management and how does these inputs vary across a variety of FW treatment and valorization technologies. Furthermore, Kibler et al.'s (2018) third question referred to these inputs compare to the energy and water embedded in the food through its production phase. Last, the study was interested in understanding how grey water (non-consumptive) production during treatment processes could be compare to blue and green water (consumptive) use during food production. These questions were key in the design and the conception of this study.

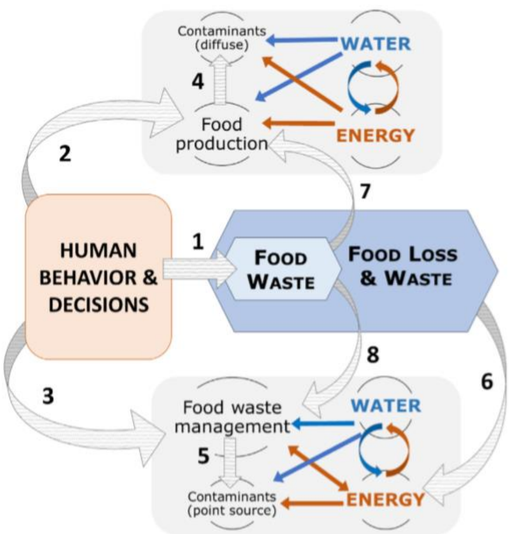

Figure 1: Kibler et al's. (2018) conceptual model of Food Waste's Interactions with the FEW nexus.

To analyze how FW interacts with the FEW-nexus several existing tools can be used, notably Life-Cycle Assessment (LCA) studies.

2.7. LCA as a Tool to Converge FW Studies with a FEW-Nexus Perspective

Several LCAs studies have been of particular interest to create an implicit convergence between FW studies and a FEW-nexus approach.

Optakun et al. (2017) performed an LCA comparing anaerobic digestion, pyrolysis, and an integrated energy system (combination of anaerobic digestion and pyrolysis). Their findings highlight the energy and water use of the three FW treatments processing, offering important insights for a FEW-Nexus approach to FW recovery.

Levis et al. (2011) provide an overview of the energy use of different alternatives from landfill, to anaerobic digestion, to composting, each with various level of complexity (e.g., bioreactor or not for the landfill). The study found anaerobic digestion as the least energy intensive FW treatment, particularly due to the avoided electricity production from other energy sources (Levis et al. 2011). It is interesting to note that landfilling combined with a bio-reactor for energy recovery fairs particularly well in term of total energy use while most composting technics (e.g., windrows, gore composting system) are the most energy intensive. This is due partly for the lack of energy offsetting and due to several energy-intensive features such as the odor control ventilation (Levis et al., 2011).

Tom et al. (2016) explored the energy use and water footprint of different diets in the US. As detailed in their supplementary information, the study performed a meta-analysis of LCA studies to find the energy use (MJ/kg) and the water footprint (l/kg) of a wide-range of food products. These types of studies are crucial to develop a thorough overview and understanding of water and energy uses along the FSC and lay the path for a FEW nexus perspective in food studies.

Additionally, Beratta et al. (2017) building on a previous MFA of food losses along the Swiss FSC, performed an LCA to identify the environmental hotspots of FW occurring in the FSC. They found that most FW treatment processes are far from offsetting the environmental impacts that occurred earlier in the production and processing stages, with the notable exception of cereal FW turned into animal feed (Beratta et al., 2017)

Last, Corrado et al. (2017) laid the foundation for a systematic methodology to adopt for FW-related LCA studies. One of their main recommendations related to the definition of FW into three categories: avoidable FW, unavoidable FW, and total FW. This characterization of FW is adopted in this thesis research. Furthermore, their finding suggests a tendency of current LCA practitioners to underestimate the overall environmental burdens of FW. Finally, their study highly recommends the inclusion of FW treatment processes in the system boundaries. It can also be noted that their paper has the rare particularity to discuss explicitly IE application for FW recovery.

Conclusion

Overall, the FEW-nexus approach is very promising in the context of FW and the bio-based economy. Yet, aside from Kibler et al.'s conceptual approach on FW within the FEW nexus perspective, little work has been done to quantitatively assess the FW flows and connect them with the FEW nexus flows. Furthermore, few studies have quantified the amount of wasted energy and water through FW (Cuellar et al., 2010; Vanham et al., 2015).

In addition, although FW processing technologies have been assessed based on their environmental performances, few have been reviewed explicitly from a FEW nexus perspective.

Last, the current frameworks to guide the strategy of FW management (e.g., FWMH, *Value Pyramid)* are lacking comprehensiveness and coherence to address the management and valorization of FW flows.

There are therefore several gaps in FW studies; a systemic overview such as FEW nexus is lacking to characterize the FEW implications of urban FW flows; the lack of assessment to identify synergies and trade-offs between the different FW treatment and valorization options; and the lack of an overarching and comprehensive framework to guide FW valorization strategies.

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3. Methodology

A combination of methodologies was used throughout this thesis to answer the research question and its sub-questions. First, the FW issue from Amsterdam had to be understood through the lenses of FEW nexus approach. Second, the FW flows within the city had to be quantified using a Material Flow Analysis. Then, the embedded energy within each food type defined in this study were quantified using LCA studies, while the water footprint literature was used to quantify the embedded water in every food type considered. Furthermore, to explore the different FW valorization technologies, the lenses of the bio-based economy was used. A systematic review of the LCA literature on treatment technologies was needed to quantify the energy and water inputs of every technology selected from the inventory. Finally, a strategic framework had to be developed to understand which valorization technologies will be appropriate in the context of Amsterdam and from a FEW perspective.

3.1. Food Waste and the Food-Energy-Water Nexus.

First, a thorough literature review was performed to fully develop an understanding of the FEW nexus approach. The seven guiding questions developed by Daher as a starting point of FEW-Nexus studies were used to correctly frame the FW issues of Amsterdam within the FEW-Nexus perspective (Table M1). These questions help highlight the intersections of the food, water, and energy systems involved in FW, specifically:

- Food-Energy Linkages
- Food-Water Linkages
- Water-Energy Linkages

Daher's framework and the exploration of the three types of linkages were key to answer the first sub-question of this thesis.

Table M1: Daher's Seven Question for FEW-Nexus
1-What is the critical question?
2-Who are the players/stakeholders
3-At what scale?
4-How is the system of systems defined?
5-What do we want to assess?
6-What data is needed?
7-How do we communicate it? Where do we involve the decision-maker in the process?

3.2. Amsterdam Food Waste MFA

One of the main goals of this thesis is to quantify the FW flows within Amsterdam's municipality, therefore a Material Flow Analysis (MFA) was used to achieve this goal.

An MFA is an analytical tool that assesses the flows of materials through a defined system, and which is based primarily on mass balance (inputs equal to outputs and change in stocks) (Allesch & Brunner, 2015).

An MFA was particularly suited to provide a physical accounting of a flow such as FW and support waste management decision-making (Allesch & Brunner, 2015). In other words, an MFA provided an understanding of the metabolic rate (ton/year) of FW flows and their origins within the city's boundaries.

3.2.1. Goals and System Definition

The goal of the MFA was to quantify the FW flows stemming both from households and from companies producing FW. The system's boundaries are the geographical boundaries of the city of Amsterdam (Fig.M1). The only flow under study in this MFA was therefore FW.

Following the CREM's methodology, FW flows at the household levels, are divided between avoidable food waste (AFW) and unavoidable FW (UFW) (CREM, 2010; CREM, 2013; CREM, 2017). For example, if one prepares an onion for cooking, the skin removed from the onion during its preparation is considered UFW, while the rest of the onion, if thrown away, is considered AFW. FW flows at the household level are further disaggregated into food types. Food types ranges from vegetables and fruits, to meat, to chocolate and sweets (Table M3).

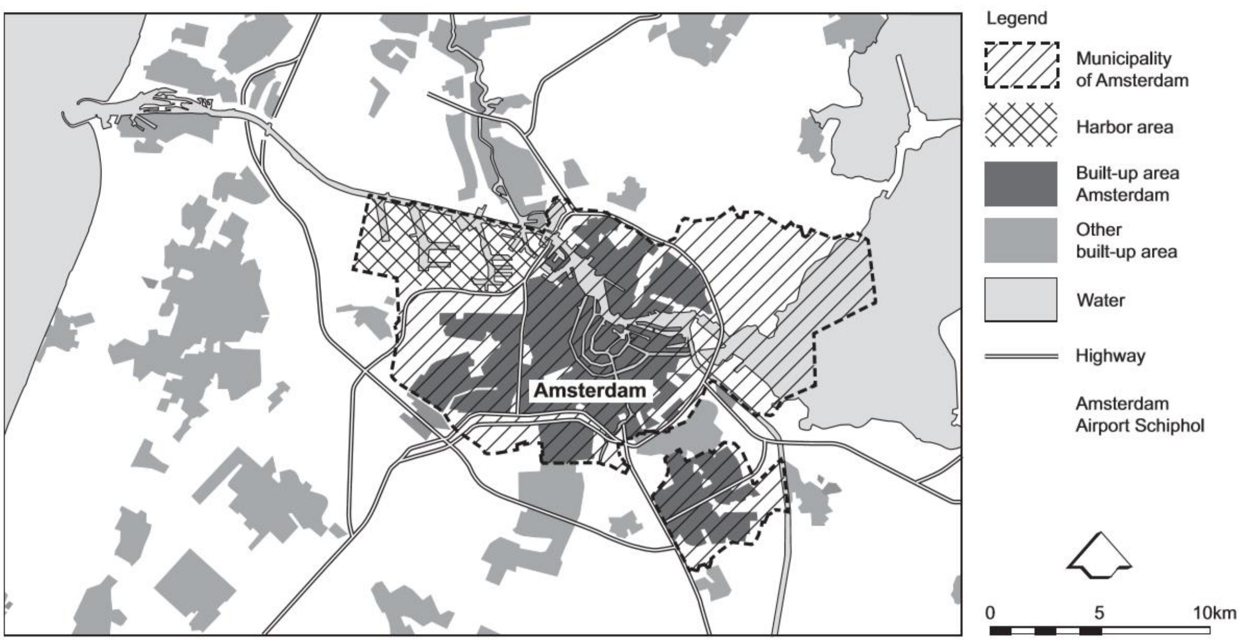

Figure M1: Amsterdam's Municipality Boundaries (From Voskamp et al. 2017, p.890)

Time

The majority of the data used to construct the FW MFA stemmed from the year 2016. Therefore, the MFA illustrates the state of the FW flows in Amsterdam in 2016.

3.2.2. Inventory & Modelling

The modelling approach chosen for this MFA is based on MFA Accounting, where substances flows are quantified and monitored.

As mentioned earlier, there are two main sources of FW in the city of Amsterdam. Therefore, two approaches had to be taken to acquire accurate data for the households' FW flows and companies' FW flows.

Regarding household FW data, it is mostly based on four studies synthesized by the Dutch Nutrition Center (Voedingscentrum), while the companies FW data stems from the work of the REPAIR (*Resource Management in Peri-urban Areas*) research group. This research group has been aiming over the past two years to create a geo-design spatial mapping tool to connect waste streams at a regional scale. The metropolitan area of Amsterdam (AMA) was chosen as one of their case studies, with a focus on organic waste (including food waste).

Table M1: Data Source Summary

Data Source	**Household or Companies Model**	**UFW and AFW categorization**
Voedingscentrum (2017)	Household	Yes
CREM (2017)	Household	Yes
Kantar Public (2017)	Household	Yes
REPAIR (2018)	Companies	No
Welink (2015)	Companies	No

Household Data

The household data for the MFA originate from the Dutch Nutrition Center that combined four bottom-up studies to achieve a detailed picture of the FW generated at the household level in the Netherlands (Voedingscentrum, 2017).

At the household level, there two main waste streams for FW, namely residual waste and organic waste (referred to as GFT). The former refers to mixed waste originating from a household, and entailing the absence of hazardous material, and removed recyclable materials (Sahimaa et al. 2015). The latter entails all organic waste such as a food peeling and garden waste.

In the following paragraphs, the methods used by the Nutrition Center to generate the household FW data is explained.

First, the bottom-up dataset developed by CREM offers the possibility to quantify precisely the amount of FW per person at the household-level in the Netherlands. The CREM research team collected the FW from households located in 13 municipalities (including Amsterdam).

As the CREM team performed the same study repeatedly over three years (2010, 2013, 2016), their findings over the years offer an accurate picture of the waste produced at Dutch households. The CREM team quantified the amount of FW by food types, both in the residual and GFT waste streams. The CREM team differentiates FW by UFW and AFW (CREM, 2017). The following equation represent the basic approach to FW quantification:

$FW = UFW + AFW$ (Equation 1)

The Nutrition Center integrated the findings of the CREM team with two other reports performed by the consultancy Kantar Public (Voedingscentrum, 2017).

The first one aimed to better understand the other FW disposal routes at the household-level. Based on self-reporting questionnaire (using the structure developed by the CREM team), the Kantar Public team was able to quantify for each food category, the frequency of wastage and the different routes used to dispose of the FW (Table 3) (Voedingscentrum, 2017). It is important to note that household self-reporting underestimated by half the amount of FW produced per person (Kantar Public, 2016). Nonetheless, the report offered insightful results for the disposal routes. The large sample group used in this analysis made these results especially reliable (Voedingscentrum, 2017).

The second report by Kantar Public was commissioned by the Dutch Dairy Association (NZO) to quantify dairy wastage and by extension all liquid FW wastage at the household-level. This report gave insights in the disposal routes and the amount of wasted fluid liquid (e.g., milk, coffee) and thick liquid (e.g., yogurt) (TSO/Kantar Public, 2017).

Table M2: Average FW Disposal Routes for All Food Categories (TSO/Kantar Public, 2017)	
Route	**Frequency in %**
Residual	35.00%
GFT	25.20%
Sink	25.10%
Outdoor Animal (ducks, birds, deer)	5.30%
Toilet	4.50%
Other	2.10%
Household's Pet	1.50%
Composting Heap	0.80%
Outdoor Trash Bin	0.40%

Finally, the Nutrition Center used a study performed by the market analysis institute *GfK* to quantify the amount purchased per food item in Dutch households (using again the food categories defined by the CREM team) (Voedingscentrum, 2017).

By using the integrated results of the CREM and Kantar Public reports for FW and the purchased food amount by food categories, it was possible to calculate the share of unavoidable, avoidable, and consumed food products by food categories.

As the Nutrition Center report's results only provided the amount of food purchased at the household-level per food type, the total of avoidable FW (AFW) per food type, and the share of avoidable FW (AFW) per food type *already* adjusted for the unavoidable FW (UFW), the fraction of overall UFW still had to be calculated.

First the food bought per food category was calculated per person instead of per household. In their study, the Nutrition Center considered one household to be composed of 2.2 people. Thus, the amount of food purchased per person was calculated with the following equation:

$$B_{pp}(Food_{type}) = \frac{B_{hh}(Food_{type})}{2.2} \quad (Equation\ 2.1)$$

Where:

B_{pp} is the amount of food bought in kilogram per person per year for the chosen food type.

B_{hh} is the amount of food bought in kilogram per household per year for the chosen food type.

Next, as previously explained the Nutrition Center presented the fraction of AFW per food type already adjusted for the UFW from the food purchased, that is, that the study subtracted the UFW from the overall food purchased per food type. This relationship can be summarized by the equation (E 2.2)

$AFW_{f\_adjusted}(Food_{type}) = \frac{AFW\ (Food_{type})}{B_{pp}(Food_{type}) - UFW(Food_{type})}$ (Equation 2.2)

Where:

$AFW_{f\_adjusted}$ is the adjusted fraction of avoidable FW relative to the amount of food bought for a chosen food type *minus* the unavoidable FW.

AFW is the amount of avoidable FW per kilogram per person for a chosen food type.

B_{pp} is the amount of food bought in kilogram per person for a chosen food type.

UFW is the amount of unavoidable FW in kilogram per person for a chosen food type.

To find the amount of UFW for a chosen food type:

$AFW_{f_{adjusted}} * B_{pp} - AFW_{f_{adjusted}} * UFW = AFW$ (Equation 2.3)

$AFW_{f_{adjusted}} * UFW = AFW_{f_{adjusted}} * B_{pp} - AFW$ (Equation 2.4)

$UFW = B_{pp} - \frac{AFW}{AFW_{f_{adjusted}}}$ (Equation 2.5)

Equation 2.5 yields the total amount of unavoidable FW for a chosen food type bought. To find the fraction of UFW for a chosen food type purchased:

$UFW_f = 1 - \frac{AFW}{AFW_{adjusted} * B_{pp}}$ (Equation 2.6)

UFW_f is the fraction of unavoidable FW in the amount of food bought for a chosen food type.

The non-adjusted AFW fraction for a chosen food type was calculated with the equation:

$AFW_f = \frac{AFW}{B_{pp}}$ (Equation 3)

With the amount of food purchased by food type, and the fraction of UFW and AFW for the chosen food type, the MFA for the FW flows from the households in Amsterdam Municipality can be calculated by multiplying by the overall population of the city.

$B_{Amsterdam}(Food_{type}) = B_{pp} * Population_{Amsterdam}$ (Equation 4)

For the AFW:

$AFW\ (Food_{type}) = \ B_{Amsterdam}(Food_{type)} * AFW_f$ (Equation 5)

For the UFW:

$UFW\ (Food_{type}) = \ B_{Amsterdam}(Food_{type)} * UFW_f$ (Equation 6)

In their work on organic waste in the AMA, the REPAIR team not only calculated the amount of a FW produced by companies but also by the households in the area. The research group also used the CREM reports as basis for the quantification of FW flows from the households. Yet, they added another data layer to perform a consistency check in the quantification of FW production per person. Specifically, the research team used a dataset compiled by CBS, which contains the average value of household waste per inhabitant per urbanization level.

The urbanization level is a good indicator to reflect the amount and type of waste produced at the neighborhood-level (REPAIR, 2018). Urbanization levels range from 1.0 to 4.0. The urbanization level can therefore be used as a consistency check to correctly quantify the amount of GFT and residual waste at the household level in the AMA (REPAIR, 2018). This consistency check was not used in this thesis as more than 90% of the households are represented by the same urbanization level (i.e., level 1.0). The variation in the production of FW per household according to their district urbanization level is therefore deemed negligible for Amsterdam Municipality.

Companies Data

Companies located in the municipality also produce a substantial amount of FW. As mentioned earlier, the dataset representing the amounts of FW generated by companies in Amsterdam originates from the work performed by the research group REPAIR. As their whole study area was the AMA, data specifically related to Amsterdam municipality had to be selected. The data for Amsterdam's companies was extracted from the larger REPAIR dataset using basic filtering options present on the Excel software. The company FW dataset is built from top-down datasets, but also use some bottom-up data.

The first step entailed downscaling national data from an unpublished joint report by CBS and Wageningen, which estimated the amount of FW produced in tons by the food processing, manufacturing and food service industries. The study provided a level of detail to the NACE levels 2-3 for these industries. NACE (*Nomenclature Générale des Activités Économiques de la Communauté Européenne*) codes represent economic sectors, which can be very aggregated (level 1) or very disaggregated (level 4) in terms of details of the description of the economic activities. This study used by the REPAIR team was able to generate this data by using micro-data from EURAL-codes. EURAL codes are a catalogue of approximately 840 different waste materials, partly sorted by origin, specifically by industry or business activity (REPAIR, 2018).

They subsequently estimated the different shares of FW production among the food processing and manufacturing sectors from collected waste surveys and the Eurostat's food plug-in (REPAIR, 2018). This plug-in is based on members state voluntary filling in the List of Waste codes for the European Waste Categories 09.1 and09.2.

FW 09.1 refers to Animal and mixed food wastes from food preparation and products, including sludges from washing and cleaning; separately collected biodegradable kitchen and canteen waste, and edible oils and fats (Hanssen et al. 2013). FW 09.1 originates from food preparation and production (agriculture and manufacture of food and food products) and are considered non-hazardous.

FW 09.2 refers to vegetal wastes from food preparation and products, including sludge from washing and cleaning, materials unsuitable for consumption and green waste. FW 09.2 originate from food and beverage companies (Hanssen et al. 2013). The Eurostat plug-in data management process enables overall to determine FW productions for the different food-related NACE codes, and divide them into two streams, 09-1 and 09-2.

The second step aimed at downscaling the average FW production of the national food sectors (NACE codes) to the company-level in the AMA (REPAIR, 2018). First, the REPAIR team calculated the total number of Dutch employees in 17 food-related economic sectors (NACE codes). Within Amsterdam, only 13 of these sectors are present. For each sector, the numbers of employees present in this sector in the AMA is divided by the total number of employees in this sector in the entire Netherlands. This process yields the share of the national FW tonnage that is produced by companies in the AMA. This FW tonnage is then distributed among the companies of the same sector by their number of employees (REPAIR, 2018).

3.3.3 MFA Interpretation

This MFA interpretation stage entailed the characterization of the main sources of FW within the Amsterdam municipality. Furthermore, a special focus on the largest food type waste flows is given with the goal of scoping down to specific eco-innovations and bio-based recovery practices tailored to these large flows.

3.3. Quantifying the FEW Nexus of Amsterdam's FW flows.

3.3.1. Embedded Energy in FW Flows

The emdedded energy use refers to the cumulated energy used in every step of the supply chain, from the production at the farm till the preparation at home (i.e., till cooking if applicable).

The embedded energy within the FW flows was calculated using a meta-analysis from Tom's et al. (2016). The study compiled a little less than 400 entry for energy use of a range of food products. To adapt the energy use to the Dutch and European context, studies not relevant to the geographical area considered in this study were filtered out. Furthermore, studies published before 2000 were removed if more recent studies were available.

Despite the wide scope of the dataset, data for *coffee*, *tea*, *biscuits*, and *chocolate* were lacking. Thus, an LCA study by Konstantas et al (2018) on *chocolate* products sold in the UK was used. For the energy use of different types of *biscuits*, the work of Konstantas et al. (2013) was selected as it provided a thorough modelling of the biscuit supply chain in the European context. For *tea*, a study by Munasinghe et al. (2017) on tea production in Sri Lanka was used. Their study included the consumption of tea, and Sri Lanka is the third exporter worldwide of tea. Their work was therefore considered consistent with the other studies. Last, a study by Hassard et al (2014) was selected for *coffee*'s energy use. Although, the production of coffee occurred in Japan, it reviewed a wide variety of coffee products and their findings reflected the general energy use along the entire coffee supply chain. It was therefore deemed suitable for the energy use of *coffee*.

Each food product was classified within their respective food categories (as defined by CREM, 2017) and an average value for each food categories was then calculated to obtain the embedded energy in each specific flow highlighted in the MFA (Table M3). The entire table (Table A2) containing all the LCA studies used for the calculation of the average is present in the Appendices.

About half of LCA studies cited (Table M3) used a farm-to-fork system boundaries (production, processing, distribution, retail-to-household, and preparation), although a few of them used farm to consumer-house boundaries, and a very few used farm to processing-gate boundaries. For example, Carlsson-Kanyama et al. (2003) calculated the energy use for both cooked and fresh meat.

This may add to some uncertainties relative the calculations of embedded energy for a given food type that may be prepared (i.e., cooking meat, fish, vegetables, rice, potatoes, and pasta) within the FW flows analyzed. Yet, the CREM reports accounted for the amounts of AFW prepared, unprepared, and untouched (in packaging), illustrating the various state of the food thrown away. In 2010, they found that about 32% was prepared, about 50% was unprepared, and the rest was untouched (CREM, 2010). There is therefore a slight discrepancy in terms of system boundaries, though it would have moderate impact on the overall energy profile of the FW flows, considering all types of stages (prepared or not) were considered in the averages, similarly to the CREM methodology.

Table M3: Summary of Embedded Energy per Food Type		
Foot Categories	**MJ/kg**	**Sources**
Tea	129	Munasinghe et al. 2017
Coffee	54	Hassard et al. (2014)
Cheese	53	Broekema and Kramer, 2014; Carlsson-Kanyama et al, 2003;
Fish and Seafood products	40	Foster et al, 2006 ; Svanes et al, 2011 ; Pelletier et al, 2009 ; Carlsson-Kanyama et al, 2003 ; Thrane, 2004 ; Iribarren et al, 2010 ; Almeida et al, 2015 ; Aubin et al, 2009 ;
Meat products	36	Williams et al, 2006; Carlsson-Kanyama et al, 2003; Cederberg, 2003; Leinonen et al, 2012; Prudêncio da Silva et al, 2014; Carlsson-Kanyama and Faist, 2000; Saunders and Barber, 2009
Soups & broths	25	Average (Meat and Vegetables)
Chocolate and Sweets	23.9	Kostantas et al. 2017 ; Kostantas et al. 2018 ; Carlsson-Kanyama et al, 2003
Other food products	21.7	Average (excluding Coffee & Tea)
Sauces and Fats	18	Carlsson-Kanyama et al, 2003 ; William et al, 2006
Preserved pastry goods, biscuits, and cakes	16.6	Carlsson-Kanyama et al, 2003 ; Foster et al, 2006 ; Kostantas et al. 2017
Vegetables	16.4	Cellura et al, 2012 ; Canals et al, 2008 ; Carlsson-Kanyama et al, 2003 ; Raghu, 2014 ; Ueawiwatsaku et al, 2014 ; Almeida et al, 2014 ; Williams et al, 2006 ; Saunders and Barber, 2008
Eggs	15.4	Pelletier et al, 2013 ; Carlsson-Kanyama et al, 2003
Dairy products	15.4	Broekema and Kramer, 2014 ; Foster et al, 2006 ; Nilsson et al, 2010
Fruits	9.4	Carlsson-Kanyama et al, 2003; Coltro et al, 2009; Girgenti et al, 2013; Peano et al, 2015; Blanke and Burdick, 2005
Rice	8.5	Carlsson-Kanyama et al, 2003
Fresh bread	6.2	Braschkat et al, 2003
Pasta and other farinaceous products	5	Carlsson-Kanyama et al, 2003
Potatoes	4.2	Williams et al, 2006; Mattsson and Wallen, 2003; Foster et al, 2006; Carlsson-Kanyama et al, 2003

3.3.2. *Embedded Water in FW flows*

The embedded water refers to the cumulated water used throughout each step of the life-cycle of a food product.

The embedded water within the FW flows was calculated using a variety of sources, namely Vanham et al. (2015), Mekonnen & Hoekstra (2011;2012), Miah et al. (2018), Chapagain & Orr (2010) (Table M4).

These studies calculated the water footprint of main food type, both accounting for green water (i.e. precipitation, water in the vegetation) and blue water (ground and surface water abstraction). Grey water was not considered in this water footprin.

Mekonnen & Hoekstra (2012) provided local data on the water footprint for animal products produced in the Netherlands.

Concerning the water footprint of fish and seafood products, it is often considered that sea products directly coming from the sea do not have a water footprint (Hoekstra, 2015; Vanham et al. 2015). Yet, as half the seafood consumed in the world stems from aquaculture (FAO, 2016), the water footprint of the aquaculture cannot be neglected. The understanding of the embedded water from this sector is still highly limited (Hoekstra, 2015), yet by considering the feed inputs and the water required for the production environment, Hoekstra estimated that the fish aquaculture could use about 4500 liters of water per kilogram of fish produced. As not all seafood products consumed in Dutch households' stem from aquaculture, the global average consumption (50% of seafood from aquaculture) was taken as a proxy, and therefore the fish and seafood's water footprint was calculated by halving in two the estimate from the aquaculture 's water footprint (Table M4). The water footprint of the seafood products is therefore considered to be highly uncertain, and further research ought to be performed to refine the estimate.

The water footprint of *soup and broths* were calculated using an average of the WF of *meat*, *fish*, *vegetables*, and *other products*. It is therefore not a precise estimate. Considering the system boundaries, the majority of studies included the production stage, but also the processing stage for processed food such as *pasta*, *bread*, or *biscuits*. However, the production stage of most food types has an overwhelming impact of the overall water footprint. Thus the subsequent processing stages and the inclusion or not of the water used during preparation by consumers have often neglectable impacts on the overall emdedded water profile (Mekonnen & Hoekstra, 2011).

Table M4: Summary of Embedded Water per Food Type (Production to Processing)			
Food Type	**Water Footprint in L/kg (or m3/ton)**	**Region**	**Source**
Coffee	18292	Global	Mekonnen & Hoekstra, 2011
Meat Products	8166	EU	Vanham et al. 2015
Tea	8130	Global	Mekonnen & Hoekstra, 2011
Sauces and Fats	6235	EU	Vanham et al. 2015
Other Food Products	3729	EU	Average (derived from all other food types)
Soups & Broths	3585	EU-Uncertain	Average (derived from meat, vegetable, fish, and other products)
Cheese	2502	NL	Mekonnen & Hoekstra, 2012
Fish and Seafood Products	2250	EU-Uncertain Estimate	Hoekstra, 2015
Eggs	1830	NL	Mekonnen & Hoekstra, 2012
Pasta and other farinaceous products	1639	Global	Mekonnen & Hoekstra, 2011
Rice	1486	Global	Mekonnen & Hoekstra, 2011
Fresh bread	1425	Global	Mekonnen & Hoekstra, 014
Chocolate and sweets	1180	UK	Miah et al. 2018
Fruits	535	EU	Vanham et al. 2015
Dairy Products	513	NL	Mekonnen & Hoekstra, 2012
Preserved pastry goods, biscuits & cakes	366	UK	Chapagain et al. 2010
Vegetables	193	EU	Vanham et al. 2015
Potatoes	174	EU	Vanham et al. 2015

3.4. Inventory of FW Treatment Technologies from the Bio-based Economy Perspective

An inventory of the currently used treatment and valorization technologies in Amsterdam as well as a review of the current food rescue initiatives taken place in the city were performed to assess the current situation of Amsterdam vis-à-vis FW management.

The inventory developed was based on Amsterdam municipality website, the REPAIR reports, news articles, and local online blogs, the latter ones especially useful to identify local social initiatives.

The latest literature review performed by Nayak et al. (2019) on the main valorization strategies regarding FW was then used as a guiding frame to explore the different options available. The four technological strategies identified were: energy valorization, value-added chemicals, biomaterials, and bio-adsorbents. Amsterdam's current FW treatment strategies were then characterized in the light of these four strategies.

To assess the initiatives' FW rescue potential, that is their ability to recovery large amounts of FW at the city-scale, a qualitative scoring system was developed. The six aspects considered were: *price incentive, users reach, infrastructure and technology needed, ease of use, social impact,* and *FW awareness* (Table M5).

First, it was assumed that *price incentive* would increase the potential of FW rescue, which is consistent with the literature (Hooge et al. 2017; Schane et al., 2018). Furthermore, the need for infrastructure and technologies for setting-up a rescue scheme was assumed to add logistical constraints, and therefore act as barriers for setting-up a successful rescue initiative (Mourad, 2016). The *ease of use* for users to access or be part of the rescue initiatives was also seen as an important element of the success (in term of scale) of a recovery initiative (Michelini et al. 2018).

The number of potential users (i.e., *user reach*) was also deemed a very important parameter, as logically more users entail more FW rescue potential (in terms of quantity). To mark the importance of this scoring category, a doubling factor was assigned to the *user reach* scores, essentially doubling the weights of these scores relative to the other scoring categories.

Finally, two other score's categories were created; *social impact*, that is the capacity of an initiative to generate social interactions, and *FW awareness*, which entails the educational role of the initiative vis-à-vis FW issues. Both were also deemed important components, although successful FW rescue initiatives may not need to highly score in these categories to rescue important volumes of FW. Therefore, these two scoring categories were assigned a halving factor, essentially dividing by two their weights compared to the other scoring categories (*price incentive, infrastructure and technology needed,* and *ease of use*), and by four for the *user reach* category.

Limitations of this scoring system are discussed later on in the discussion section (Cf. Chapter 8). The assessment was done after reviewing the mode of functioning of each individual rescue initiatives, using the same sources mentioned above. The ranking of FW rescue potential was done through simply summing the scores of each category and accounting for their weighting factors.

Table M5: Qualitative Scoring System for Food Waste Rescue Initiative.						
Score	**Weighting Factor**	**0**	**1**	**2**	**3**	**4**
Price Incentive	1	Normal Pricing	Sales (Store)	Discounts (large)	By-Donations	Free
Users Reach	2	0-20	20-200	200-1000	1000-5000	5000+
Infrastructure & Technology Needed	1	Food Processing Plant & Specialized Processing /Storage/ Transport Equipment	Cooking and Storage Spaces & Processing Equipment	Physical Space, Simple Cooking Equipment	Data Servers/ Application Ubiquitous technologies (phone, laptop)	No Infrastructure or Technology/Basic Website
Social Impact	0.5	No social interaction	Some social interactions	Food Market	Neighborhood Dinner	Special attention to vulnerable groups (elderly, low-income, children)
Ease of Use	1	Strict (location/ time/ product selection)	Less Strict (location and/or time and/or product selection)	Somewhat Flexible	Flexible	Very Flexible (pick-up anytime, may select FW products)
FW Awareness	0.5	No Awareness	Mentions of FW Issue	Information about FW	Events (Debate, screening)	Workshops/ Educational Material

3.5. Quantifying the FEW Nexus Requirements for FW Treatments Processes

Data on treatment and valorization technologies had to be collected to assess the energy and water requirements of these technologies. 12 technologies were selected for this step, covering the four valorization strategies identified by Nayak et al. (2019).

The LCA literature once again offered a key range of sources to draw from to derive estimate of energy and water use for these technologies. This step yielded a rough picture of the amount of water and energy inputs required for a given technology for the valorization of FW in Amsterdam. Table M6 presents the 12 technologies and the main data sources used for each of them.

Table M6: Technology Reviewed and their Data Sources	
Technology	**Source**
Anaerobic Digestion	Ecoinvent 3.5
Composting	Ecoinvent 3.5
Biofuels	Ecoinvent 3.5
Pyrolysis	Yang et al. 2018
Incineration (Biomass)	Ecoinvent 3.5
Incineration (Mixed Municipal Waste)	Ecoinvent 3.5
Value-Added Chemical: Pectin	Pfaltzgra et al. 2013
Value-Added Chemical: (hydroxymethyl)Furfural	Lam et al. 2018
Enzyme	Ecoinvent 3.5
Bio-Adsorbent	Arena et al. 2016
Bio-Polymer	Harding et al 2007
BSF Bioconversion – protein feed and compost	Mondello et al. 2017

3.6. Quantifying the Amount of Recoverable Resources and Their Economic Values

The quantities of resources and products extracted from the use of the 12 technologies presented above are quantified using the same data sources presented in Table M6.

Then, the prices of these resource were determined thanks to LCA studies, industry reports, and specialized websites. Table M7 presents a summary of the prices of these valuable resources, and their data sources. These values may vary due to changing market trends, but represent strong estimates for these products, and therefore illustrate an accurate order of magnitude in terms of economic value.

Regarding woody tar's pricing, the price of coal tar was used as a proxy as woody tar would be a direct replacement for this product; and no strong estimate was available for this specific product.

The amounts of products extracted by each technology were multiplied by their market prices to determine the economic output produced from valorizing one ton of FW. This step thus presents a simplified economic assessment of these technologies as it considers simply the potential revenues from the resources extracted, but also the costs associated with the energy and water inputs (see input costs in Table A4, Appendices). Infrastructure, labour and any other operational and capital costs, as well as taxes and subsidies schemes are not considered due to the scope of this study.

Table M7: Summary of estimated revenues from the sales of products derived from FW valorization				
Product	**Amount**	**Unit**	**Source**	**Valorization Strategy**
Electricity	0.065	€/kWh	Jungbluth & Chudacoff (2007)	Energy
Electricity (from biogas- 40% efficiency)	0.06	€/kWh	Gebrezgabher et al. (2010)	Energy
District Heating (syngas burning or steam)	0.08	€/MJ	Jungbluth & Chudacoff (2007)	Energy
Woody Tar	0.413	€/kg	CEIC (2018)	Energy
Bio-Char	2.34	€/kg	Jirka & Thomlison (2013)	Energy/Bio-adsorbent
Biofuel (ethanol)	1.16	€/l	Jungbluth & Chudacoff (2007)	Energy
HMF (furfural)	1520	€/kg	Molbase (2015)	Value-added Chemicals
Pectin	12.35	€/kg	Pfaltzgra et al (2013)	Value-added Chemicals
PHB	2.21	€/kg	Roland-Holst et al. (2013)	Bio-material
Compost	0.04	€/kg	Lim et al. (2016)	Bio-material
Enzyme	6.27	€/kg	Liu et al. (2016)	Bio-material
BSF Protein Feed	5	€/kg	AllAboutFeed (2018)	Feed/Biomaterial

3.7. A Strategic Framework for FW Management and Valorization

A new framework is suggested by this study to guide strategies for the treatment and valorization of FW. This framework is based on the *Value Pyramid* from the Dutch-based bio-based economy framework, the FW management hierarchy (FWMH) framework developed by Papargyropoulou et al. (2014) and on FEW indicators (FW, water, energy inputs). This new framework offers a comprehensive and coherent framing of the FW issues.

The framework is applied to Amsterdam case in order to generate strategies for the prevention and rescue of its AFW and the valorization of its UFW. During this last step, the most promising technologies for the context of Amsterdam are selected among all of the technologies assessed in the previous chapter. This selection is performed by assessing the expertise of waste stakeholders present in the city, the level of development of these technologies, the types of UFW available in Amsterdam, and the FEW performances of these technologies derived from the previous chapter.

3.8. *Food Waste Stakeholders Importance and Roles*

This study considers the importance and the potential roles of FW-related stakeholders in the establishment of a future FW management scheme in Amsterdam.

The power/interest matrix developed by Newcomb (2003) was used in order to identify the interest and importance of the different stakeholders for the implementation of a FW valorization strategy for Amsterdam (Fig. M2). This matrix helps identify which are the key stakeholders that will act as strong proponents, and which stakeholders will need to be brought on board on such a project. It also enables to visualize which stakeholders may have the capacity to influence the design, implementation, and ultimately the success of a future FW scheme.

Figure M2: Power-Importance Matrix from Newcombe (2003)

Additionally, to understand better the potential roles that Amsterdam's stakeholders may play in a future FW management and valorization program, the role-stakeholder matrix developed by Tennyson (2011) is adopted in this study (Table M8). Note that the description of each role in Table M8 were developed by this study, although the descriptions of the *Influencer* and *Disseminator* roles were adapted from Tennyson (2011).

Table M8: Stakeholder-Role Matrix from Tennyson (2011)	
Role	**Stakeholder**
Partner *A core decision-maker, very active in the implementation of the project.*	
Contractor *Accomplishes key tasks in the project.*	
Influencer/Champion *Uses reputation to establish an authoritative profile to the project.*	
Disseminator *Act as advocate and advertise the benefits and merits of the project.*	
Funder *Contributes financially to the project.*	
Informer/Consultation *Provides bottom-up information and feedback on the project's outcomes.*	
Knowledge Provider *Provides key information to facilitate decision-making.*	
Regulator *Ensures the legality and the enforcement of the project activities*	
Beneficiary *Benefits from the project outcomes.*	
Other	

3.9. Reflections on the FEW Nexus Perspective and Recommendations for Amsterdam

A general discussion reflects on the findings of this study, assessing the advantages and limitations of the FEW nexus perspective to study FW issues, and providing future research opportunities. Based on the results, it also offers several recommendations for FEW Nexus and FW research practitioners.

Furthermore, in light of the insights developed throughout this study, recommendations are developed for the municipality of Amsterdam in order to support the establishment of a FW strategy.

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Chapter 1 - Framing Amsterdam's Food Waste Case Study within the FEW Nexus

Excerpt from Daher et al. (2017, p16):

'[FEW] Nexus is not a magical term; it is a philosophy that guides the navigation of a holistic resource modeling platform that enables decision-makers to build their integrative resource plans on the basis of specific, identified needs and interests. Those decision makers vary in scope and capacity: they could be making decisions at small association, local, regional, national or international levels. So do their interests and the complexity of their critical questions differ. The challenge of the WEF nexus modeling philosophy is providing those interested decision-makers with clear, simple, yet comprehensive answers. Consequently, it is unrealistic to expect a single modeling approach to fit all interests, at different scales. Instead, modeling approaches of WEF nexus issues should be built case by case, but guided by the same philosophy."

Introduction

This chapter presents the answers to Daher et al.'s (2017) seven guiding questions to guide the integration of the FEW nexus perspective within this study. Thus, these questions are used to set Amsterdam's case study within this FEW nexus context. The seven guiding questions were developed to be adaptable to the multifaceted problems requiring a FEW nexus understanding (Daher et al. 2017). The following guiding questions are:

1-What is the critical question?
2-Who are the players/stakeholders
3-At what scale?
4-How is the system of systems defined?
5-What do we want to assess?
6-What data is needed?
7-How do we communicate it? Where do we involve the decision-maker in the process?

1) What is the critical question?

The need to define appropriate technologies and initiatives that will recover FW while not adding or shifting the burden onto the energy and water systems of the city is the main driver behind using the FEW nexus perspective. The FEW nexus perspective is used to further one's understanding of where synergies and trade-offs may be uncovered among the intersections of the three systems. The critical question to be answered in the context of the FEW nexus perspective is:

What are the appropriate technologies and initiatives for the city of Amsterdam to recover the most important FW flows from a FEW nexus perspective?

2) Who are the stakeholders?

There is a large number of stakeholders within the food system of Amsterdam. Figure 1.1. illustrates the main stakeholders relevant in the context of FW flows in Amsterdam.

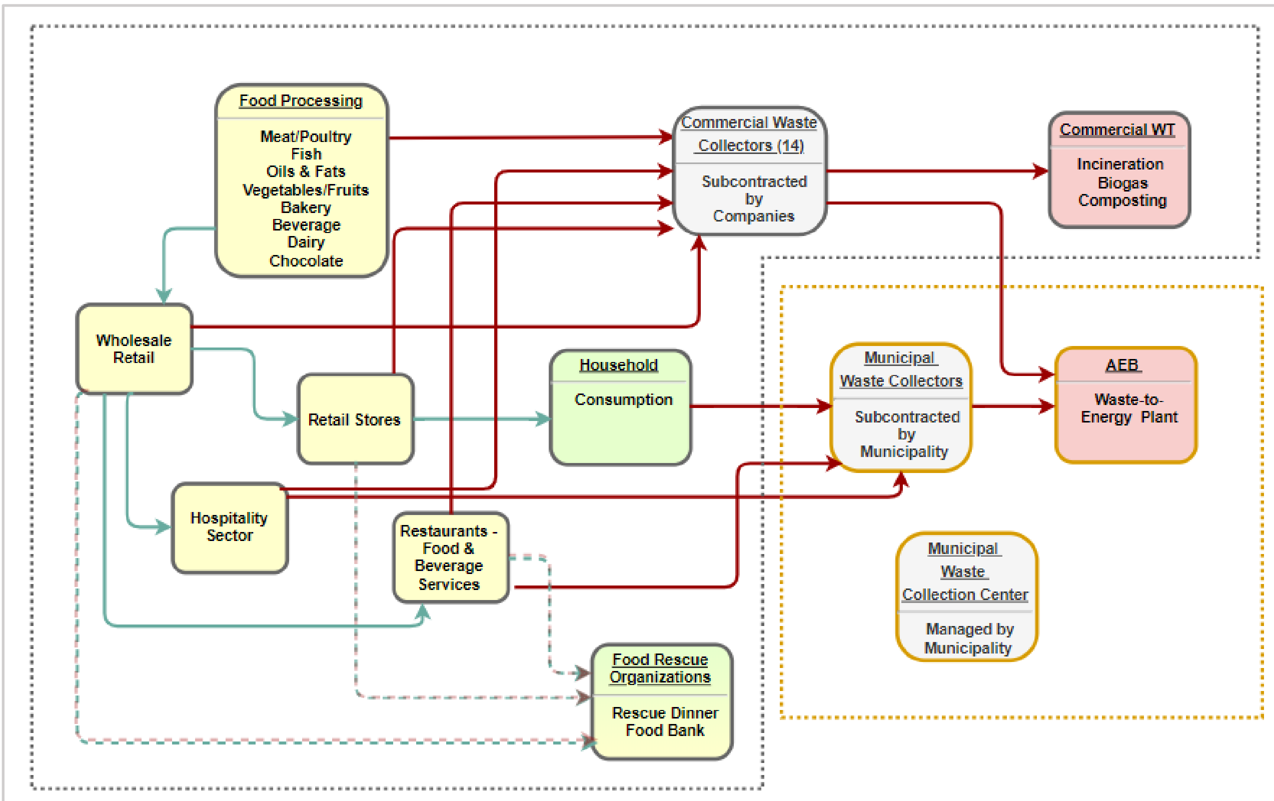
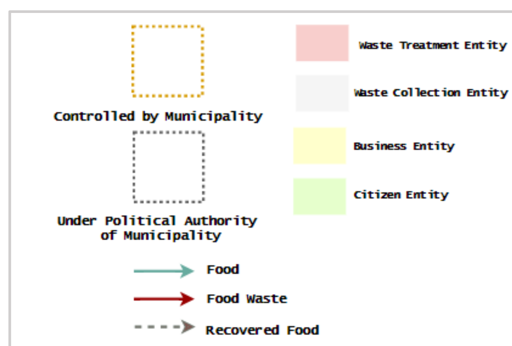


Figure 1.1: Stakeholders in Amsterdam FW Management System



Municipality

The Municipality of Amsterdam is in charge of defining and enforcing the waste management system of the city. It has the authority over all other stakeholders that produce FW and dictates when, where, and how one may or may not dispose of their FW. The municipality is also directly in charge of the waste collection centers, the household residual waste (GFT waste is not collected in Amsterdam), and it controls AEB, Amsterdam main Waste-to-Energy plant (AEB, 2007).

Furthermore, the administration also gives the authorization to commercial waste collectors as well as commercial waste treatment plants to operate in the city. The municipality is the most important stakeholder due to its interests in achieving the city's circular goals, improving its waste management practices, and its overarching authority over the local FW management system (Gemeente Amsterdam, 2018).

AEB Waste-to-Energy Treatment Plant

The AEB Waste-to-Energy produces 1 million MWh of electricity per year for about 320, 000 households, and generates about 600, 000 GJ of heat used within Amsterdam (hot water and heating).

The plant has been at the forefront of resource and energy recovery, which makes it one of the most efficient W-to-E plants in the world (AEB, 2018) (~30% efficiency). Overall, AEB processes 1,4 million tons of waste every year. The municipality holds a 100% of the shares of the WT plant (AEB, 2007).

Due to its strong and consistent engagement in developing and implementing innovative ways to recover value from Amsterdam's waste streams, AEB may be a stakeholder of substantial importance to re-design the FW recovery system of Amsterdam.

Municipal Collection Centers

There are six collection centers in Amsterdam, specifically two in the East district, one in the South district, one in the North District, and two in the West district. Although, their primary waste supply is bulky waste from households (e.g., construction, electrical waste), as well, as garden waste, there are important actors in the waste management system of the city. They are currently managed by the municipality (Gemeente Amsterdam, 2018). Collection centers may play a role in the establishment of FW recovery centers.

Waste Collector Subcontracted by the Municipality

The municipality of Amsterdam subcontracts the collection of residual household waste to private companies. These municipal waste collection companies are under the direct authority of the municipality. They represent key actors as they are the first step in the recovery chain of FW from households.

Households

There are currently 833, 420 inhabitants in the municipality of Amsterdam. Every household generates about 78 kg of FW per person per year (37kg of UFW and 41kg of AFW). As it will be shown in Chapter 2, Amsterdam's households are the largest generators of FW in the city. They represent a crucial leverage point, both for the prevention of AFW and the recovery of UFW.

Food Processing Companies

There are many different food processing companies in Amsterdam. Table 1.1 presents the different food processing sectors present in the municipal area, and the number of companies within each sector.

Table 1.1: Amsterdam's Food Processing Companies by Food Sector	
Food Processing Sector	**Numbers of Companies**
Meat and Poultry Products Manufacturing	12
Fish and Seafood Products Manufacturing	2
Vegetables and Fruits Processing	3
Oils and Fats Products Manufacturing	3
Ice Cream and Dairy Products Manufacturing	4
Bakery and Farinaceous Products Manufacturing	167
Other Food Product Manufacturing (include cocoa, chocolate, coffee, tea, and prepared meals)	33
Beverage Manufacturing	23

The food processing companies are important stakeholders as they may generate important amount of specific food components in high concentration (e.g., cocoa shells). Furthermore, food processing companies are required to contract a commercial waste collector to dispose of their important amount of waste, which represents a non-negligible overhead cost for them. Thus, it may be in their interests to valorize their FW streams to create a new source of revenues and avoid waste fees.

Due to their size and their potential highly-concentrated FW flows, the food processing companies in Amsterdam may represent an important group of stakeholders to develop a strategy for FW recovery.

Commercial Waste Collector

According to the REPAIR research group, there are currently 14 commercial waste collectors operating in the Amsterdam Metropolitan Area (AMA). It is surprisingly difficult to get an overview of these companies as waste data from companies is extremely sensitive (REPAIR, 2018). Two known waste collectors that can be cited are Renewi and Suez Netherlands (who owns a treatment plant). The commercial waste collectors are key bridging actors for FW recovery.

Certain actors, such as Renewi, may already have the recovery of valuable materials from the waste they collect as their main business mission, while some may neglect the recovery aspect of waste. Commercial waste collectors represent the first recovery step for commercial FW and are thus key actors to ensure that the flows are not cross-contaminated by other waste streams that may impede FW recovery processes.

Commercial Waste Plants

There are several commercial waste plants in Amsterdam, these companies, such as Orgaworld (part of the Renewi group), process an important amount of FW from companies located in Amsterdam. They may be key partners for the development of a city-wide strategy of FW recovery, especially due to their "sink" role of highly concentrated commercial FW.

Food Retail

The food retail stores of Amsterdam are the main food suppliers for Amsterdam's households. There are currently 1017 entities performing food retail activities within the municipality. As they are the primary connections between Amsterdam residents and food, retail stores may play a substantial role for the recovery of FW items, as well as for FW prevention. As it will be shown in Chapter 2, the food retail sector is also a non-negligible producer of FW at the city-scale.

Food Wholesale Retails

There are currently 755 companies in the food wholesale retail sector in Amsterdam. As these companies concentrate substantial amount of food before being distributed to retail stores and other customers, they represent an essential group of stakeholders for the recovery of resources from FW flows.

Food & Beverage Services and Restaurants

Food service and restaurants represents the largest food sector in terms of the number of companies operating in Amsterdam. There are currently 3265 companies in this sector. A large number of residents depends on these food services during the working week for their lunch, thus they represent an important food supply for the city's inhabitants. This stakeholder group can play an important role in FW prevention but also the sorting of FW in their respective businesses.

Food Rescue Organizations

Although smaller in size compared to other stakeholder groups, food rescue organizations such as *Instock*, *Robin Hood Kollektief*, and *Taste Before You Waste* represent key grassroot advocates for FW recovery.

As the recovery of FW for human consumption is the best option according to Paparygyroupoulou et al.'s FW Management Hierarchy framework, these organizations represent one of the most effective way of rescuing FW to feed Amsterdam's residents.

Furthermore, from a FEW-nexus perspective, they may represent the most efficient activity to recover FW in terms of energy and water use. Certain organizations such as Taste Before You Waste partner with large retailers (e.g., Albert Heijn) to recover unsold food items and prepare community dinners. These "food rescue" stakeholders fill also an important educational role to locally raise awareness about FW issues.

Other: Academia Research Groups and Consultancies

Academic researchers such as the one forming the REPAIR group are essential elements to develop knowledge at different scale (e.g., national, local, ultra-local. With their expert knowledge, they may advise the different stakeholders described previously.

Private consultancy agencies such as Circle Economy, Metabolic, or Kantar Public are also key knowledge partners that have the expertise and skills to derive circular and bio-based FW recovery strategies at the city-scale.

Except during survey periods or on-the-ground measurements, they are one of the only actors that are not in direct contact with FW flows within the municipality. Thus, they do not appear directly within the stakeholder map for the FW system.

As an important amount of data were generated by consultancies (CREM, 2010; 2013; 2017; Kantar Public, 2017; Circle Economy, 2016), they may play a crucial role in gaining future insights to recover FW in Amsterdam.

3) *At* what *scale?*

The scale chosen in this case is the municipality of Amsterdam. The consequences for choosing these boundaries will be further discussed in the limitation section of Chapter 8.

4) *How is the system of systems defined?*

The system defined is food-centric, meaning that the FEW nexus perspective is used primarily to solve an issue in the food system. Figure 2.2 illustrates the main connections and intersections along the FSC between the three core systems upon which human welfare is based (Mannan et al., 2018). This conceptual model helps understand better where such connections arise from a food-centric perspective.

Due to the scope of this study, a focus was given specifically to FW. Figures 2.3-2.8 illustrate where FW flows are directly in contact with the water and energy systems.

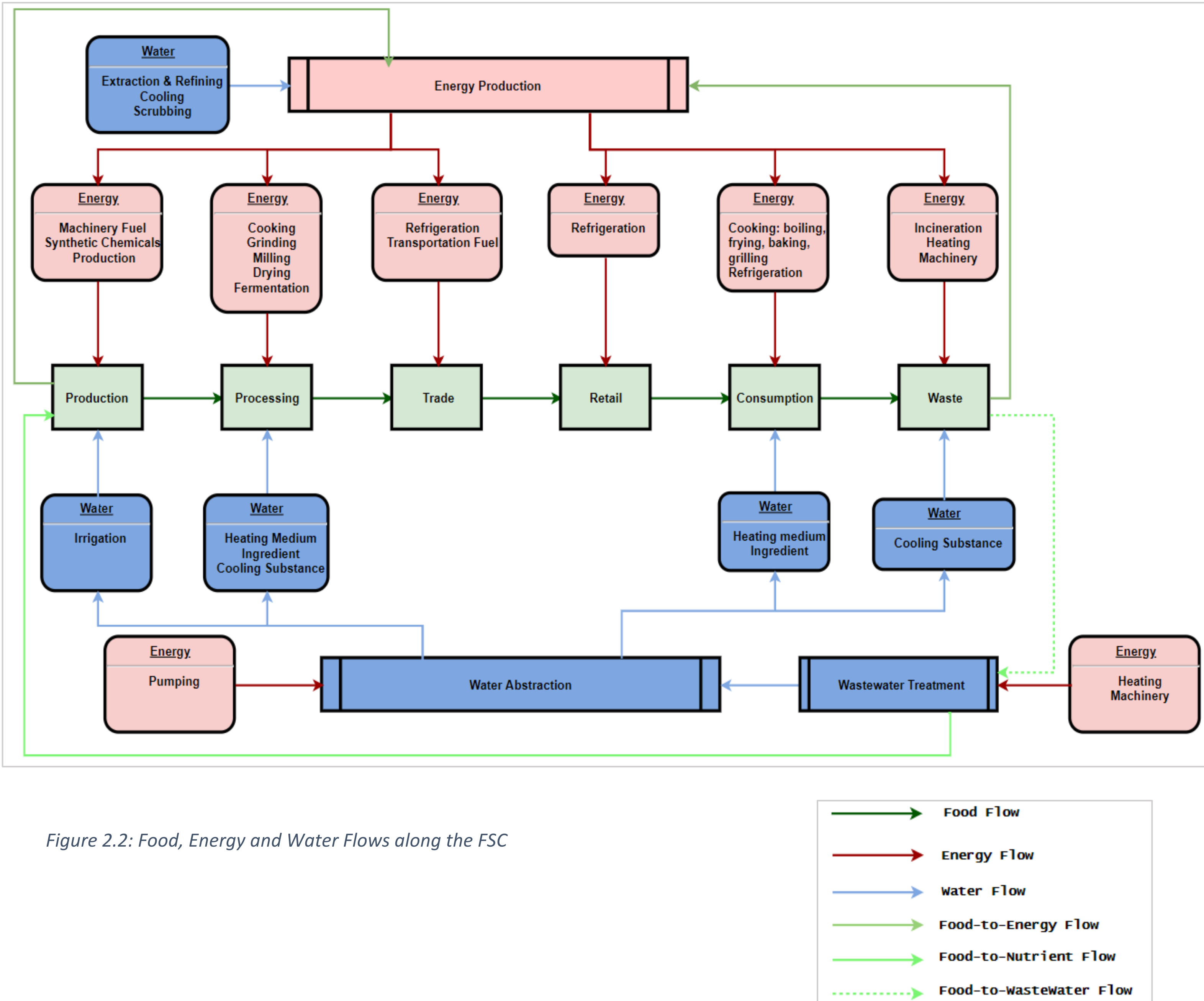


Figure 2.2: Food, Energy and Water Flows along the FSC

Figures 2.3-2.8 illustrate the main interactions between the FEW nexus for five treatment and valorization technologies. These figures are based on the results of the inventory of valorization technologies compiled in Chapter 4, and on the energy and water inputs for different technologies further quantified in Chapter 5.

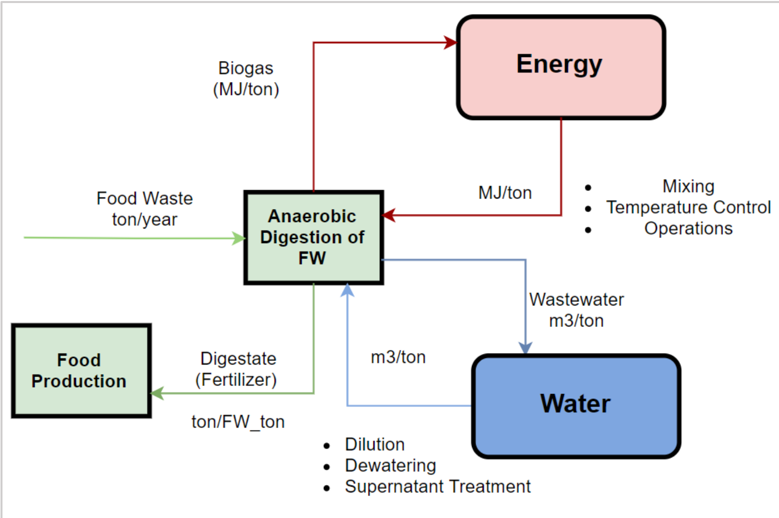


Figure 2.3: FEW interactions for FW Anaerobic Digestion.

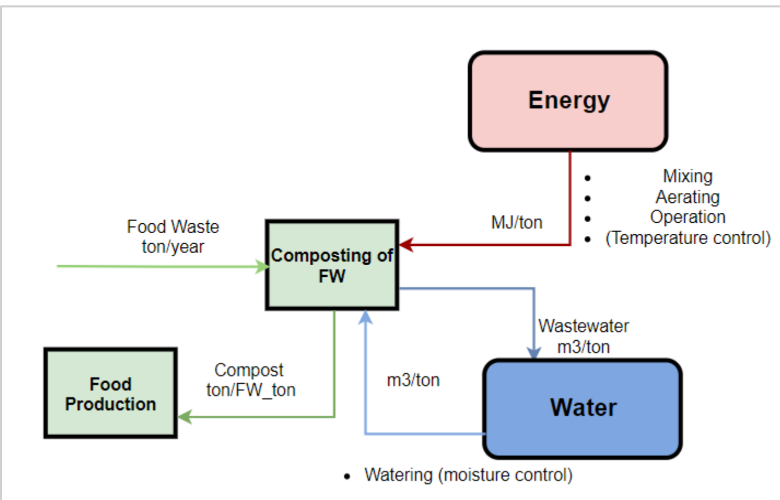


Figure 2.4: FEW interactions associated with FW Composting.

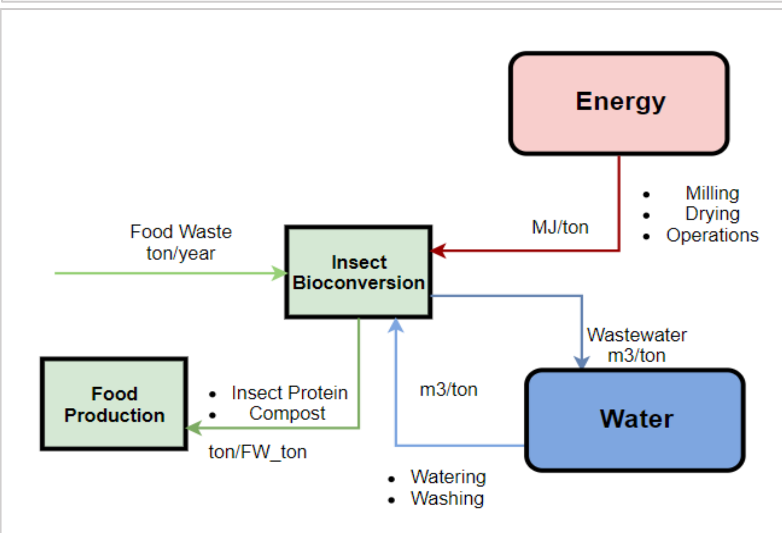


Figure 2.5: FEW interactions associated with FW Insect-based Bio-digestion.

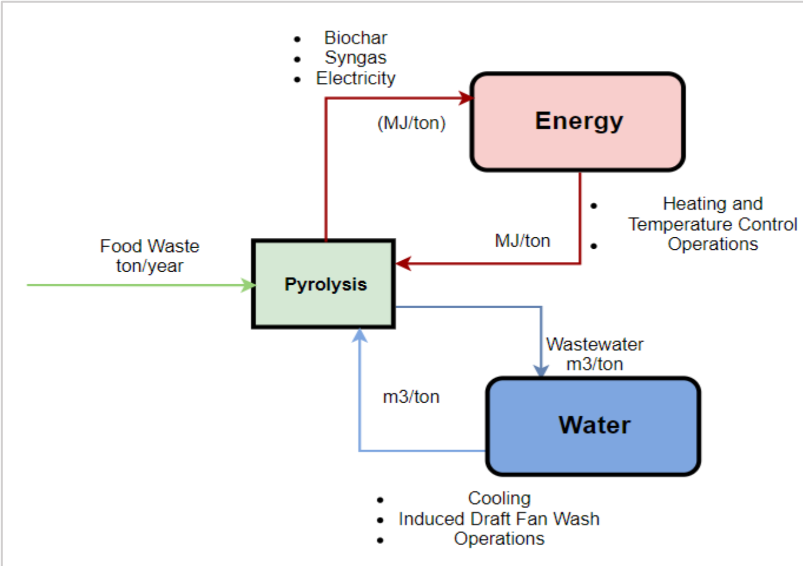


Figure 2.6: FEW interactions associated with FW Pyrolysis.

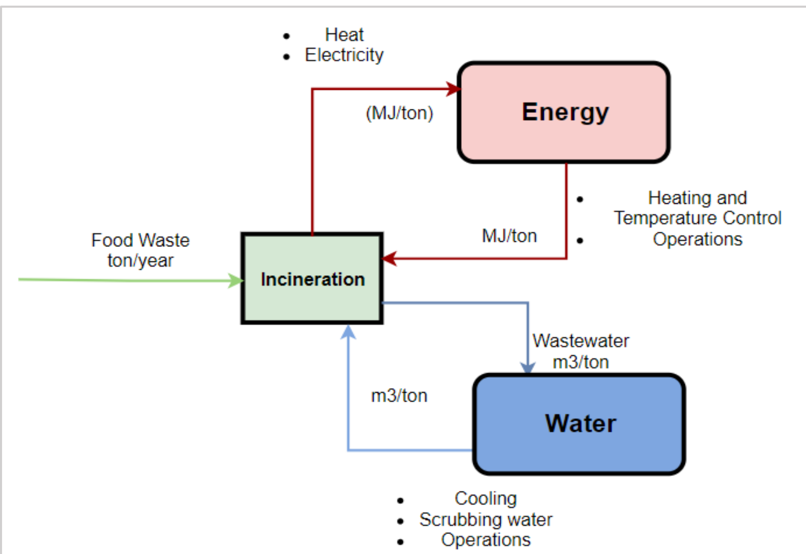


Figure 2.7: FEW Interactions associated with FW Incineration.

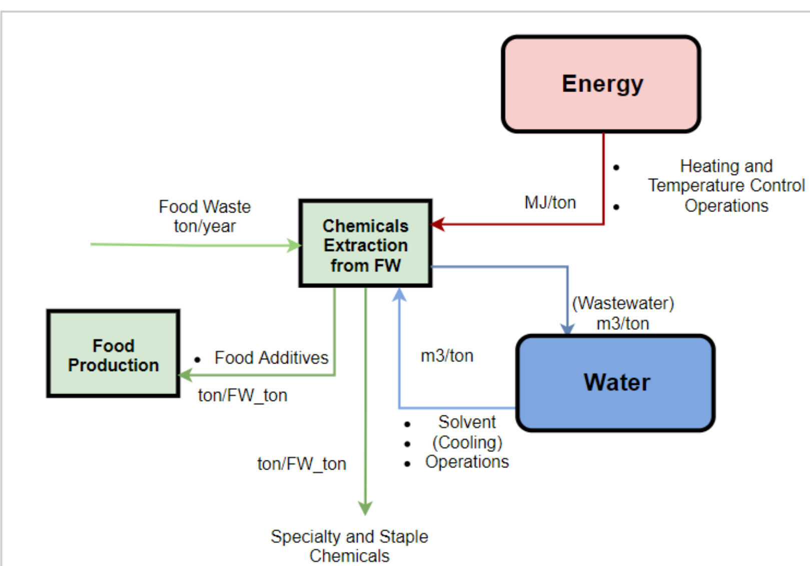


Figure 2.8: FEW Interactions associated with chemicals extraction from FW.

Figures 2.3-2.8 offer a zoomed-in illustration of the FEW interactions at the FW treatment stages. By looking more precisely into these connections, it frames the energy and water inputs to consider in this study when analyzing FW valorization and treatment technologies.

In the following three paragraphs, the connections between these systems are further described for the entire FSC (Fig 2.2), and for the FW treatment technologies (Fig 2.3-2.8).

Energy to Food

Energy is required along the entire FSC. During the production phase, energy is required for tilling, seeding, harvesting, and for the production of fertilizers and pesticides (Daher et al., 2017).

Refrigeration during transportation (e.g., cargo ships, truck) and during storage at wholesalers, retail stores, and within private household requires significant amounts of energy to extend the shelf-life of food items.

Transportation of food products by trucks, train, cargo ships, and planes may require little to enormous amounts of energy depending on the mode of transportation chosen and distances travelled. For example, the transportation of food by plane may change entirely the energy use profile of food items (Sim et al. 2007).

The energy used for processing (e.g., canning food item) but also for the final packaging represents a significant amount of the overall energy embedded in food products (Sim et al., 2007). Food processing activities may include milling, grinding, fermentation, drying, cooking, canning and more complex food preparation activities.

Last, energy is required to prepare the food before its final consumption such as for cooking (e.g., boiling, frying, baking, grilling) or cutting (e.g., small food processor) in food services, restaurants, or within private households. This last preparation step is not included in the food processing stage as it usually takes place near or at the location of consumption and is the last step before food consumption (Fig. 2.2). Final food preparation may have significant impacts on the overall energy footprint of a food item. For example, within the entire tea supply chain, it is mainly the tea preparation stage (i.e., boiling water), just prior to consume it, where most of the energy use arises (Munasinghe et al. 2017).

Furthermore, the energy inputs for the different treatment technologies and initiatives of FW is a crucial aspect for this thesis. Indeed, the energy use of FW recovery practices will be key to develop a FW strategy for the city of Amsterdam and to ensure optimal energy use concerning the exploitation of the city's FW flows. Anaerobic digestion requires energy to heat and control the temperature of during the digestion process, as well as for mixing the substrate (Fig. 2.3) (Kibler et al. 2018). Composting also requires energy to mix the compost, but also to aerate it (Fig. 2.4) (Kibler et al. 2018). Energy inputs are required to mill and dry the FW and dry the insect larvae after they bio-digestated the FW and created high-grade compost through their excreta (Fig. 2.5) (Salomone et al., 2017). Pyrolysis and incineration use energy for heat and controlling the temperature of the FW substrate (Fig. 2.6-7) (Yang et al. 2018). Valorizing FW through extracting chemicals from the FW substrate often require the heating of the FW within a solvent. Last, all of the technologies also use energy during all the other operations taking place in the infrastructures in which the technology is located.

In Chapter 2, the embedded energy for each of the main food types consumed within households are quantified. Although the goal of this thesis is not focused on reducing the energy intensity of food products, it is important to calculate the energy loss through AFW.

Food to Energy

The food inputs into the energy system stem either from the recovery of FW and its treatments through incineration (e.g. WtE Incineration), anaerobic digestion, thermal treatment (e.g., pyrolysis), and fermentation (e.g., biofuels), or from crops grown directly for biofuels production. The latter one, with the production of biofuels from crops such as maize has been a controversial connection between the food and energy system (Mannan et al. 2018). Indeed, first-generation biofuels crops have been observed as competing for the same resources (e.g., water, land) as for food crops.

Nonetheless, the production of biogas (e.g., methane), electricity, biofuels, and biochar from exclusively FW flows is an important connection that is scrutinized during the case study of Amsterdam and the exploration of FW treatment technologies (Fig. 2.3; 2.5; 2.6). The connection from energy-to-food-to-energy has been previously analyzed (Optakun et al., 2018; Levis et al. 2011), and is further explored in this study.

Water to Food

As 70% of the global freshwater use is dedicated to agriculture, the food and water systems interactions are enormous. Water is used to artificially irrigate about a quarter of global arable lands, which represent 40% of the food being consumed globally (Mannan et al. 2018).

Water is also used during food processing at various level of intensity as an ingredient or as a heating medium. For example, the beverage industry requires significant amount of water to produce their products (e.g., 150l of water for one liter of orange juice). Water is used also for food preparation (e.g., boiling pasta).

The water use of different FW recovery technologies will be explicitly explored as to understand which options are the most water-efficient. As highlighted by Kibler et al. (2018), little is still known about the FW valorization's impacts on the water system, which increases the risk of burden-shifting onto another system.

The water footprint of FW valorization technologies is thus an important aspect of this case study that will be explored extensively in the context of Amsterdam. Anaerobic digestion requires water to dilute the FW substrate, for dewatering it, and for supernatant treatments (Fig. 2.2) (Kibler et al. 2018). Composting uses water to control the moisture level of the compost, while both pyrolysis and incineration consume water for cooling (Kibler et al., 2018; Yang et al. 2018). Pyrolysis uses water to wash the draft fan (Fig. 2.4) (Yang et al. 2018). Incineration requires water for the air pollution control (scrubbing) of their flue gas. Insect (e.g., Black Soldier Fly) bio-digestion uses water to wash the insect larvae prior to their processing (Salomone et al. 2017). Water is used as a solvent to extract chemicals from FW substrate (Lam et al. 2018). All technologies may produce wastewater to a varying degree.

In Chapter 2, the embedded water (green and blue water) for each of the main food types consumed within households are quantified to assess water loss from AFW.

Food to Water

Although wastewater treatment is not the focus of this study, nutrients from food items metabolized by its consumers (e.g., through human digestion) end up in wastewater treatments. The nutrients stemming from food consumption must be removed from the wastewater flows in order for the treated water to return to the larger water system. These recovered nutrients can be a valuable resource (e.g., phosphorus) and used as fertilizers, thus returning to the food system, at the production stage (Fig 2.2).

Energy and Water

Energy is required for pumping water for irrigation and for its transportation. Energy is also required for the desalination (i.e., reverse osmosis) in water-stressed areas. Furthermore, energy inputs are required for the various wastewater treatment steps (Daher et al. 2018).

Water is also an essential input for the energy production sector, which is the second largest consumer after agriculture (Mannan et al. 2018). Water is used for fuel extraction and refining as well as for cooling and scrubbing purposes in energy production plants (Mannan et al. 2018) (Fig.2.2).

5) *What do we want to assess?*

The quantity and characterization of FW produced within Amsterdam municipality (Chapter 2) in ton/year is key to establish the foundation of this FW study. Furthermore, assessing the embedded energy and water present in the FW flows in, respectively, MJ/ton, and m3/ton is key to make the analysis comprehensive from a FEW nexus perspective.

In addition, it is required to assess the water and energy inputs of the different FW valorization treatment options, in terms of MJ/ton of FW treated and m3/ton of FW treated, for energy and water, respectively. This quantification is important to establish a FEW-efficient valorization scheme.

6) What data is needed?

The main data required was the FW production at the household-level, as well as the FW produced by companies located within Amsterdam in ton per year.

The amount of energy and water used embedded in the main food categories studied are also important data to develop an understanding of the FEW nexus. Using LCA, and Water footprint studies these data can be acquired in MJ/ton of food for energy and m3/ton for water.

Process data on energy and water use from a range of FW treatment technologies is also a key requirement for this FEW nexus case study. LCA studies and life-cycle inventories help acquire this type of data in MJ or kWh for the energy data or m3, Liter, or kilogram for water inputs. For more information on the data used for this case study, refer to the Methodology section.

In the future, as highlighted by Kibler et al. (2018), data on the water, energy and food inputs should be made available and more explicit to understand which FW valorization treatment technologies are adapted to a particular context (i.e., water-stressed region). At the moment, the input requirements are far from being comprehensibly reported and analyzed. Nonetheless, the study aims to further bridge this gap.

7) How to communicate it? Where do we involve decision-maker in the process?

The municipality of Amsterdam is one of the main decision-makers and ought to receive the main findings of this study after the end of the research process. Recommendations based on a framework using a FEW nexus perspective and considering the opportunities of valorization brought about by the bio-based economy may be a clear way to communicate the findings of this FEW nexus case study.

Other decision-makers such as AEB, food processing and commercial waste treatment plants must be informed about the different options available for the valorization of FW in Amsterdam. Once informed, they may be involved early on to further specify the FW flows they produced and treat; and help assess the practical potential of the FW treatment options for the city of Amsterdam. Consequently, these decision-makers may act as an enabling network of actors that can further develop a FW valorization scheme into a practical system.

Additionally, Amsterdam households will be a key stakeholder to communicate and involve early in the decision-making process, because, as it will be shown in Chapter 2, they are a very important source of FW. Households may therefore play an important role in the collection of the FW. In general, communicating to the consumers located within Amsterdam is a key endeavor. As important FW producers, Amsterdam's consumers. Communication campaigns under the form of flyers or brought about during neighborhood public hearings about key FW products can help bring attention to the valorization of FW, and their handlings at the household-level. A FW valorization strategy at the city-level will only be successfully implemented with some levels of engagement of the city's food consumers.

This last question brings about the importance of stakeholders in this study and merits further development and analysis, than the analytical space offered by Daher et al.'s seven guiding questions. Therefore in Chapter 7, the stakeholders related to Amsterdam's FW flows are further analyzed in order to outline more precisely their importance and role in the decision-making process and implementation of a future FW scheme.

4. Conclusion

To summarize, this chapter enabled to set Amsterdam's case study within the FEW-nexus perspective. Thirteen stakeholders were identified to be important for the development of this case study on FW. The municipality appears as the most central stakeholder considering the boundaries (i.e., the city) of this study. AEB, the waste-to-energy plant is also a key stakeholder for the waste management aspect of FW.

The main intersections between the Food-Energy-Water systems were identified at the level of the FSC, but also specifically at the FW treatment-levels. The mapping of these systems also enabled to understand the important use of energy and water throughout the FSC, and the importance of quantifying the amount of embedded energy and water within food flows to understand better their impacts on the three systems. It also reveals the variety and complexity of the possible FEW connections at the FW treatment and valorization stage, depending on the technology chosen.

In addition, Daher's questions also helped identify the main metrics to assess, namely FW ton/year, the embedded energy and water in MJ/ton and m3/ton, respectively, as well as the energy and water inputs for FW treatment, in MJ/ton of FW and m3/ton of FW, respectively.

A key takeaway from this chapter is the need to further the stakeholder analysis to better understand the importance and roles of Amsterdam FW stakeholders in the decision-making process and the implementation of a FW strategy in Amsterdam. This point is the main focus of Chapter 7.

Chapter 2: Material Flow Analysis of Food Waste in Amsterdam Municipality

Introduction

This chapter presents the results of the two MFA models developed in this study. In order to account for all FW flows in Amsterdam, this study developed two mass balance models to achieve an overall understanding of the FW flows in the Dutch city.

The first mass balance quantifies the FW produced by companies involved in Amsterdam's food system. The FW flows are divided between two FW type, namely FW 09.1, referring to animal and mixed FW, and FW 09.2, referring to vegetal FW.

The second mass balance focused on the FW flows from Amsterdam's households. This model accounts for 18 food types originating from retail stores and reaching households, and divides the FW exiting the households into AFW and UFW.

Amsterdam's Companies Food Waste Production

Figure 2.1 presents the Sankey diagram resulting from the MFA of FW flows from companies in Amsterdam. In the year 2016, companies in the food sector produced 9, 715 tons of FW. As it will be shown later on, it represents a rather small proportion relative to the FW flows produced by Amsterdam's households.

Figure 2.2 illustrates that there are three food sectors that produce the largest amounts of total FW, namely the Bakery Products Manufacturing (NACE 10.7), the Meat and Poultry Products Manufacturing (NACE 10.1), and the Oil and Fats Products Manufacturing (NACE 10.4). Table 2.1 presents the share relative to the total sectorial FW production of the largest FW producing companies within their respective food sector.

Meat and Poultry Products Manufacturing sector is the largest producer by weight of animal waste and mixed FW (09.1). This sector accounts for almost a third of the city's FW 09.1 total flows (Figure 2.2). One company, namely Abattoir Amsterdam B.V. is producing half of this food sector (by weight) composed overall of 12 companies (Table 2.1).

The Oils and Fats Products Manufacturing sector is the second largest producer of FW 09.1, with about a 22% contribution to the total FW 09.1 production (by weight). Cargill B.V., a company notably known for manufacturing soya oils, represent 69% of the totals sectorial FW output, although there are only two other companies present in this sector (Table 2.1). Two main waste streams from this sector are usually oily and fatty acids and Fuller's earth (used to bleach oils) (Welink, 2015).

The Retail Stores and Hospitality sectors are also notable FW 09.1 producers with, together, a little less than a quarter of the total FW 09.1. For either sector, there are no notable company that produces a large share of their respective total FW flows.

Regarding the FW 09.2 flows (i.e. vegetal waste), an interesting finding is the very large contribution of the Bakery Products food sector to the overall FW 09.2 production. This sector accounts for 42% of Amsterdam's total FW 09.2 flows (Figure 2.4). According to Welink's work (2015), the largest FW flows from bakery are composed of starchy substances and sugar. There is no company that appears to produce a significant share of the FW 09.2 flows from the Bakery sector. The bakery Simon Meijssen is the largest FW 09.2 producers in this sector with only a share of 4.6% of the total mass.

The Other Food Product sector is the second largest FW 09.2 generator with 17% of the total FW 09.2 flows. The DUTCH COCOA B.V. company accounts for 29% of the FW produced from the OFP sector. Cacao pods is usually the largest waste flows from this type of company (Welink, 2015). This sector features companies manufacturing prepared-meals, coffee and tea, chocolate and sugary confectionary.

Additionally, the Wholesale Retail sector has equally a significant contribution to Amsterdam's FW 09.2 production, with an overall 13% FW production share (in weight) over the total FW 09.2 produced in Amsterdam (Figure 2.4). HEMA B.V. is the largest FW producing wholesale company in Amsterdam, with over 50% of the total sectorial FW production.

Last, Beverage Manufacturing, Oils and Fats Manufacturing, and Vegetable and Fruit Processing are noticeable contributors to the total FW 09.2 production, with respectively, 8%, 7%, and 6% shares (in weight).

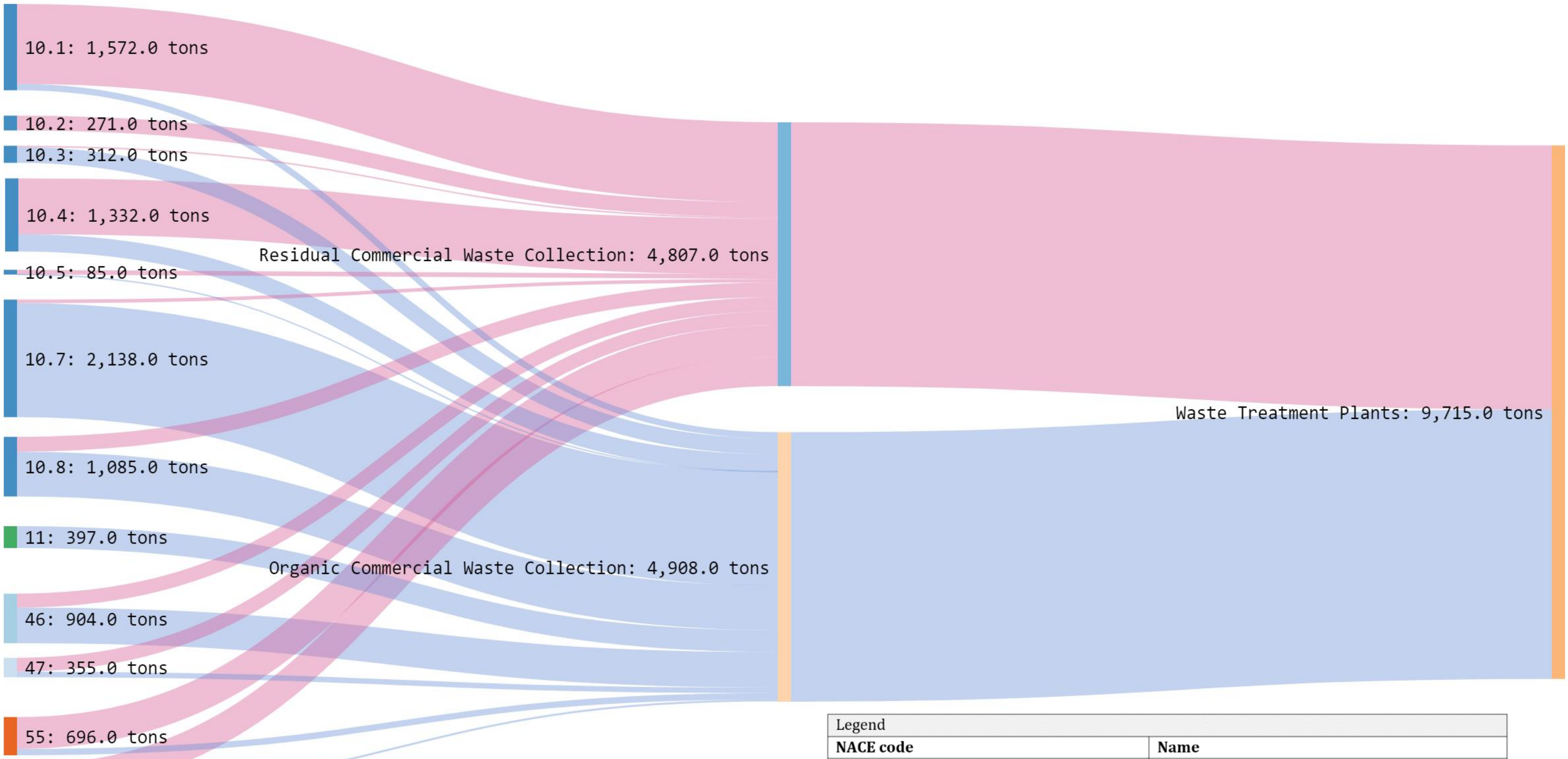


Figure 2.1: Material Flow Analysis of Food Waste Flows from Companies in Amsterdam
(RED: FW 09.1 – Animal Waste & Mixed Food Waste; BLUE: FW 09.2 -Vegetal Waste from FW)

Legend	
NACE code	**Name**
10.1	Meat and Poultry Products Manufacturing
10.2	Fish and Seafood Products Manufacturing
10.3	Vegetables and Fruits Processing
10.4	Oils and Fats Products Manufacturing
10.5	Ice Cream and Dairy Products Manufacturing
10.7	Bakery and Farineous Products Manufacturing
10.8	Other Food Products Manufacturing (include cocoa, chocolate, coffee, tea, and prepared meals)
11.0	Beverage Manufacturing
46.0	Whole Sale Retail
47.0	Retail Stores
55.0	Hospitality
56.0	Food & Beverage Services and Restaurants

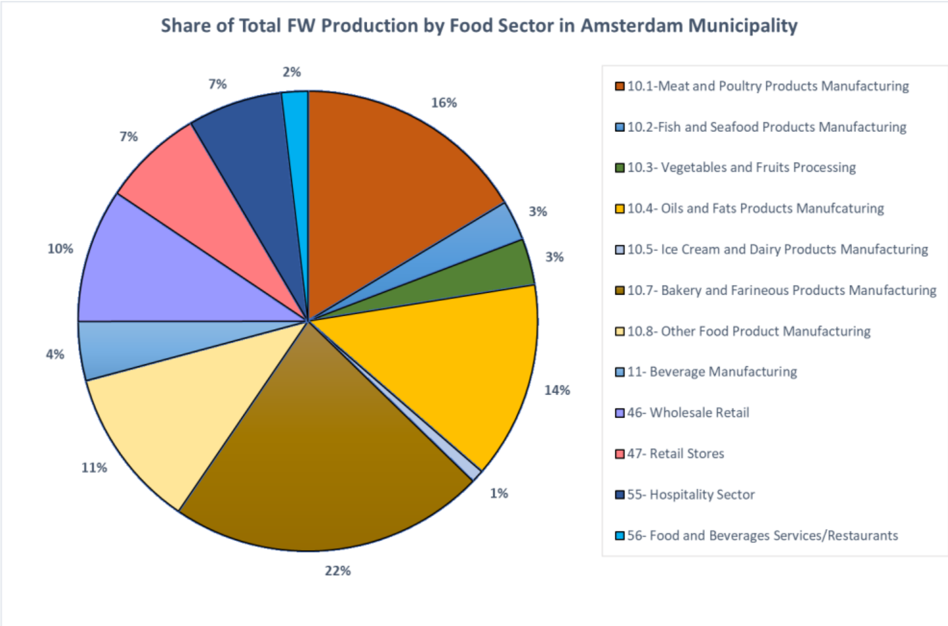


Figure 2.2: Shares of Total FW Production (in weight) by Food Sectors

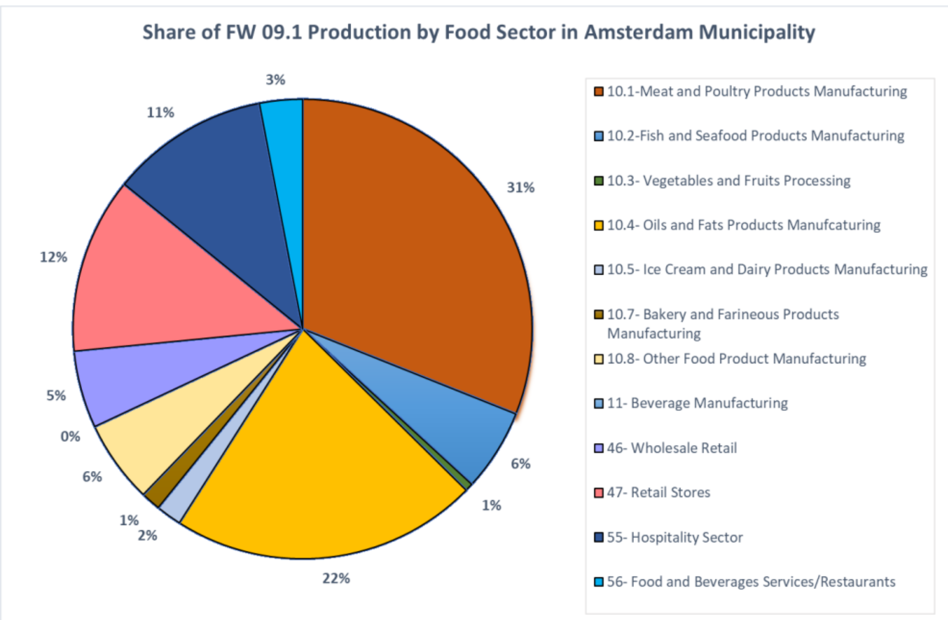


Figure 2.3: Animal Waste and Mixed Food Waste Production Shares (in weight) by Food Sectors

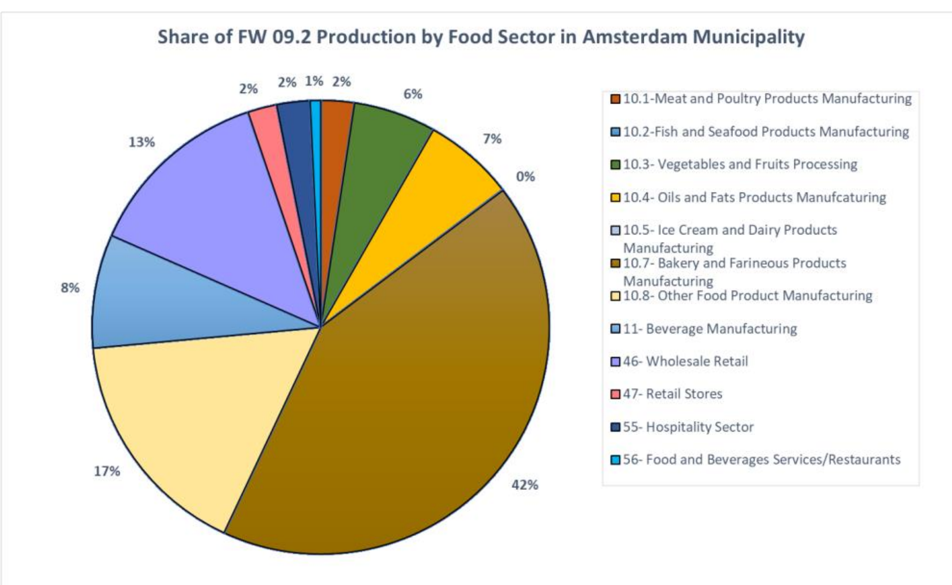


Figure 2.4: Food Vegetal Waste Production Shares (in weight) by Food Sectors

Table 2.1: Amsterdam Companies with the Largest FW production in Their Food Sector			
Food Sector	Largest FW Producer (Top 1)	FW Production Share relative to Entire Food Sector	Numbers of Companies in Food Sector
10.1	ABATTOIR AMSTERDAM B.V.	51.5%	12
10.2	ZALMHUIS STEUR B.V.	96.0%	2
10.3	THE TR8 COMPANY B.V.	55.6%	3
10.4	CARGILL B.V.	69.0%	3
10.5	G&M GELATO NATURALE B.V.	50.0%	4
10.7	BROODBAKKER SIMON MEIJSSEN B.V.	4.6%	167
10.8	DUTCH COCOA B.V.	29.5%	33
11	BROUWERIJ'T IJ	18.2%	23
46	HEMA B.V.	53.5%	755
47	ALBERT HEIJN (One store)	3.4%	1017
55	HILTON INTERNATIONAL NETHERLAND B.V.	5.9%	520
56	LA PLACE FOOD B.V.	0.7%	3265

Amsterdam Household Food Waste Production

The overall mass in tons of FW exiting Amsterdam's households for the year 2016 was determined thanks to the household MFA (Fig. 2.7). With a total of 65,000 tons of FW, it is 6.5-fold higher than the total amount produced by companies in the different food processing, retail and hospitality sectors located within Amsterdam's boundaries.

Dairy products represent by far the largest food inflows by weight into Amsterdam's households, with 68, 259 tons bought in 2016, or about 24% by weight of all inflows (Fig. 2.5). *Vegetables* and *fruits* are the second largest mass inflows, with around 33,000 tons/year each. Together, they account for almost a quarter of the purchases by weight.

Meat products and *fresh breads* are also very similar in size (around 25,000 tons) and represent the third largest flows by weight, with respectively, 8.7% and 8.9% of the total weight of food bought. *Potatoes* are also a notable inflow in Amsterdam's households, with 6.4% of the total food inflow, by weight (Fig. 2.5).

Overall, AFW represent 12% by weight of the food purchased by Amsterdam's households. On the other hand, UFW represent 11% of the amount of food bought, by weight. Thus, overall 23% of the food bought (by weight) in retail store end up in the households' residual waste.

Regarding AFW, *fresh bread* represents by far the largest stream, with 7,625 tons of fresh bread ending in the trash bin in 2016 or 22% of the overall AFW mass flow (Fig. 2.6; 2.7). *Dairy* is the second largest flow with 5,675 tons/year (16.7%), while *vegetables* and *fruits*

AFW flows are similar in size, contributing respectively, 13.8% and 11.8% (relative to total weight of the AFW flows) (Fig. 2.6).

Meat and *potatoes* represent the third largest group with 2,400 tons and 2,041 tons, respectively, which represents 7% and 6% by weight of the overall AFW production in 2016 (Fig. 2.6).

Concerning UFW, *vegetables husks and peeling* and *fruits peels* are the two largest flows accounting together for about 17,500 tons or 56% of the total amounts (in tons) of UFW produced. *Coffee grounds* are noticeably a significant flow of UFW, with a little less than 7,000 tons, or a 22% contributing share. Last, *potatoes peels* are a noteworthy UFW with 11% of the overall UFW household productions. Therefore, these four UFW accounts for 90% of the total UFW of Amsterdam.

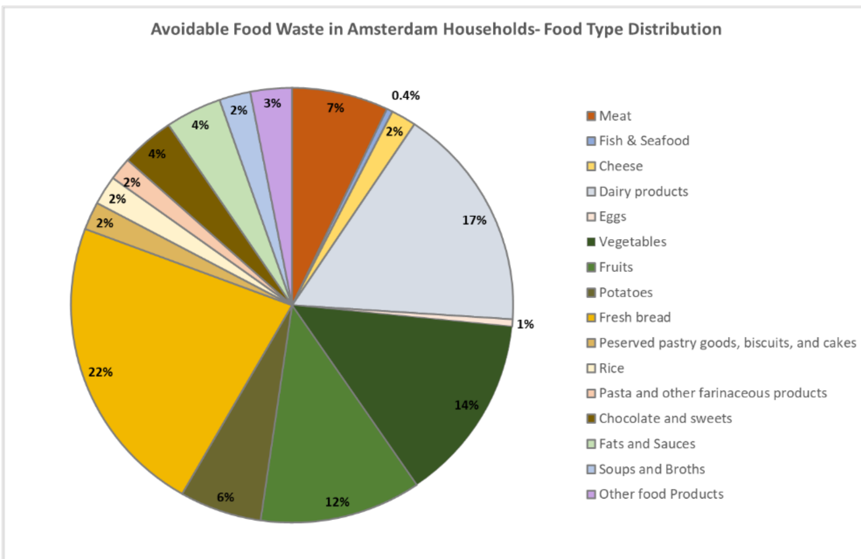


Figure 2.5: Weight distribution by food type purchased by Amsterdam households in 2016.

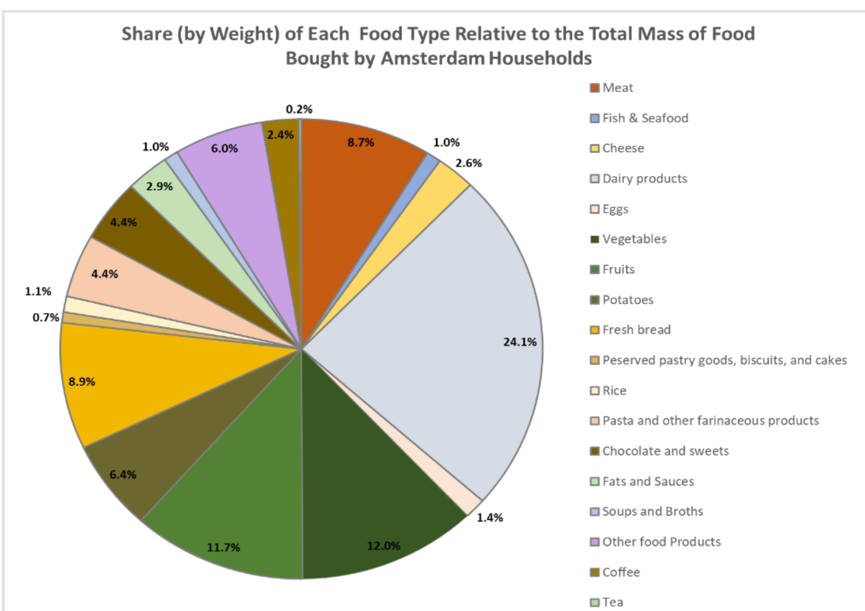


Figure 2.6: Avoidable Food Waste in Amsterdam (2016) – Weight distribution by Food Type.

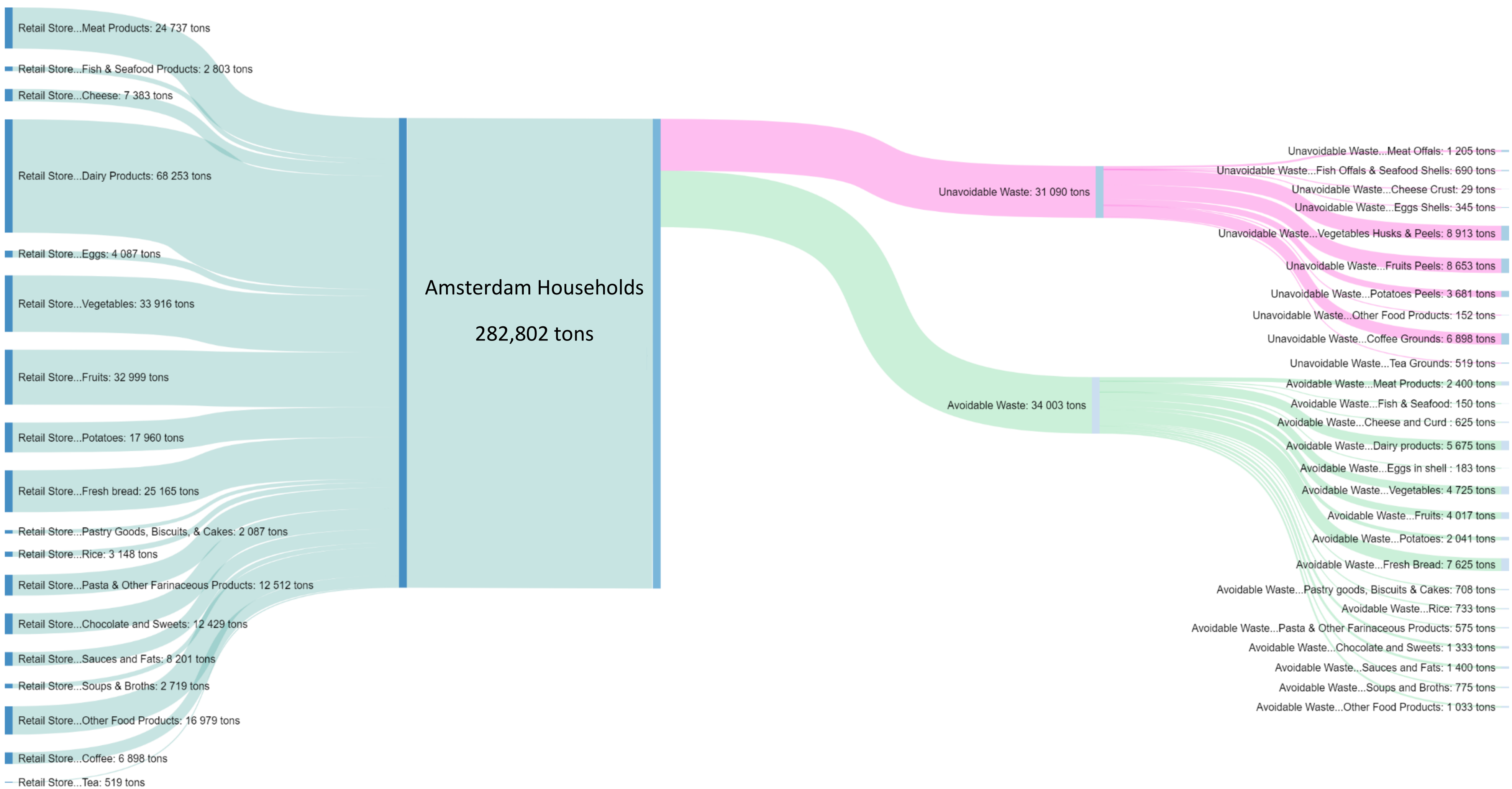


Figure 2.7.: Sankey Diagram of Amsterdam's Household Food Flows

Conclusion

This chapter revealed key insights into Amsterdam's FW flows. First, within the municipality's boundaries, households are by far the largest source of FW, relative to businesses in the different food sectors.

Second, the largest inflows by weight in Amsterdam is represented by *dairy* products, followed by *vegetables*, *fruit*, *fresh bread,* and *meat* products.

Third, the largest AFW flows are, in decreasing order, *fresh bread*, *dairy*, *vegetables*, and *fruits*. On the other hand, *vegetables husks and peels, fruits peels*, *coffee grounds*, and *potatoes peels* constitute the bulk of the total UFW flows. These results will be useful to derive recommendations for the city of Amsterdam, in Chapter 8. Indeed, as it will be shown in Chapter 4, it exists a variety of valorization and treatments technologies that can be used for specific FW flows.

Furthermore, it also helps highlight which flows of AFW could be be targeted by FW prevention campaigns, which in this case would be *fresh bread* and *dairy* products (followed by *vegetable and fruits)*.

Consequently, these results enable to outline the first features of a FW management and valorization scheme for Amsterdam. *Vegetables husks and peels, fruits peels*, *coffee grounds*, and *potatoes peels* are the main streams for UFW valorization strategy, while *fresh bread*, *dairy*, *vegetables*, *and fruits* ought to be at the core of AFW prevention and rescue strategy.

Last, it also shows that in this specific urban center, households should be a central provider role in a future FW scheme due to their major contribution to Amsterdam's FW flows. These takeaways will be further discussed in Chapter 6, 7, and 8.

Chapter 3: Embedded Energy and Water in Amsterdam's Households Food Waste Flows

Introduction

This chapter presents the results of the quantification of embedded energy and water present in the food flows reaching Amsterdam's households.

Following the MFA of the FW flows of Amsterdam, it was possible to determine the embedded energy and water footprint of these flows. To summarize, the embedded energy refers to the amount of energy that was used along the whole lifecycle of a food product until it is prepared or not at the household-level. On the other hand, the embedded water of a food product generally refers to the water input at the production stage of the food type, but also include the processing stages of processed food.

Energy and Water Inputs in Amsterdam Purchased Food Flows

Embedded Energy

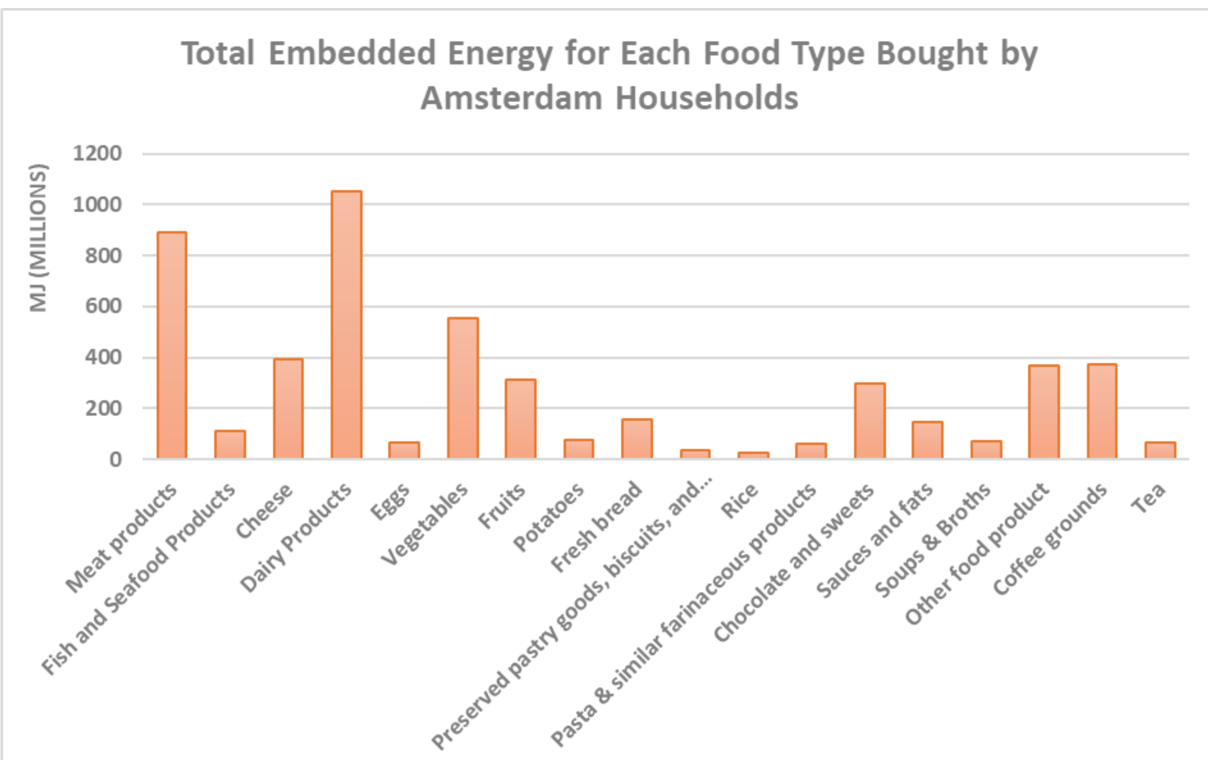


Figure 3.1: The Embedded Energy present in the Food Purchased by Amsterdam's households– The sum of each food type purchased in tons by all Amsterdam's households was multiplied with the energy intensity of their respective food type (MJ/ton).

Figure 3.1 presents the total amounts of energy embedded in each food flow, aggregating the food flows to represent all Amsterdam's households.

As shown by Fig. 3.1, the *meat* and *dairy products* are the food types with the largest amount of embedded energy, with respectively, about 890 and 1050 MJ of embedded energy present in the sum (in tons) of all *meat* and *dairy* purchases by Amsterdam's residents (Fig 3.1). The reason explaining these high energy figures for these two food types is however opposite.

Meat products have a relatively large energy intensity with 36 MJ of energy per kg of *meat* product (Williams et al, 2006; Carlsson-Kanyama et al, 2003; Cederberg, 2003; Leinonen et al, 2012; Prudêncio da Silva et al, 2014; Carlsson-Kanyama &Faist, 2000; Saunders & Barber, 2009). It is however only the fifth largest flows of purchased food by weight (in tons).

On the other hand, *dairy products* have a relatively low energy intensity with 15.4 MJ per kg of product, but they represent the largest inflow of food in Amsterdam's households, by weight. (cf. Chapter 2) (Broekema and Kramer, 2014; Foster et al, 2006; Nilsson et al, 2010). More precisely, the amount bought (in tons) of *dairy* products is 2.7 times greater than the amount of *meat* products bought, but the energy intensity of the latter is 2.3 times greater. It results therefore in having these two food types with the largest embedded energy of all the food flows coming into Amsterdam's households.

The *vegetables* purchased by Amsterdam's residents also contribute a significant amount (556 MJ) to the overall embedded energy present in the total amount of food purchased (Fig 3.1). The amount of embedded energy in *vegetable* products is relatively low (16.4MJ/kg) (Cellura et al, 2012; Canals et al, 2008; Carlsson-Kanyama et al, 2003; Raghu, 2014; Ueawiwatsaku et al, 2014; Almeida et al, 2014; Williams et al, 2006; Saunders and Barber, 2008). Yet, this high contribution is notably due to the relatively large amounts (in tons) of *vegetables* bought in Amsterdam's households (second largest purchased food type in tons after dairy products; cf. Chapter 2).

Cheese, *coffee*, and *other products* are also notable food types which have visible contributions to the overall embedded energy. For *cheese* and *coffee*, they both represent small amounts of the total amount (in tons) of food purchased in Amsterdam (respectively, 2,6% and 2.5% by weight; cf Chapter 2). However, they both have high amounts of embedded energy with 54 and 53 MJ/kg for *coffee* and *cheese*, respectively.

Regarding *other food*, its contribution is highly uncertain as its embedded energy is simply an average of all food types (excluding *coffee* and *tea*) due to a lack of reliable data. The different levels of uncertainties will be further discussed in Chapter 8.

Finally, *fruits* and *chocolate and sweets* are also worth noting for the substantial amount of embedded energy. The amount of embedded energy in *fruit* products is particularly low (9.4 MJ/kg), thus their visible contribution is entirely due to the large amounts (by weight) of *fruits* purchased in Amsterdam's households, which is similar in weight to the *vegetable* inflow (tied second largest, cf. Chapter 2).

Chocolate and sweets require a significant amount of energy throughout their life-cycles (23MJ/kg), and the amount in tons of *chocolate and sweets* products bought by Amsterdam's household is high. It results in a notable contribution to the total embedded energy of the households' food flows.

Embedded Water

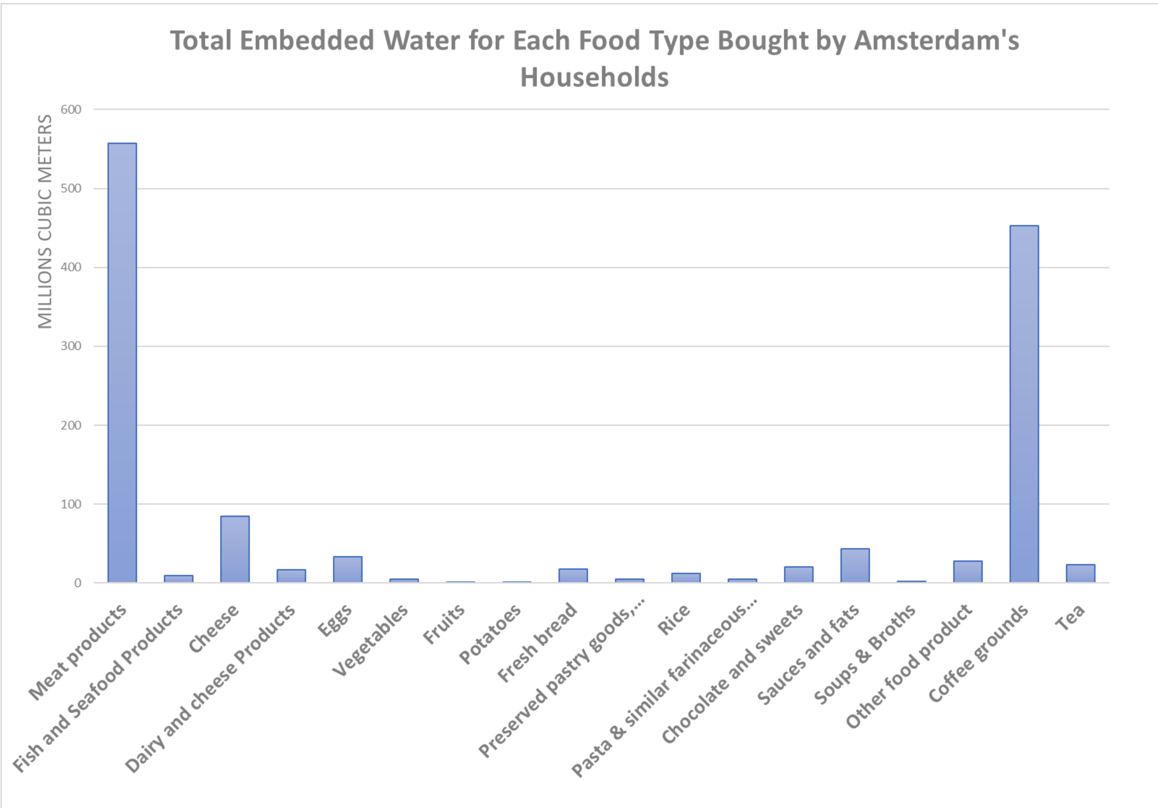


Figure 3.2: The aggregated embedded water of every food type purchased in Amsterdam's households - The sum of each food type in tons purchased by all Amsterdam's households was multiplied with their respective water intensity (m3/ton).

Regarding the water footprint of the different food types purchased by Amsterdam's households, *coffee* and *meat* products are overwhelmingly the two largest contributors to the water footprint of the total amount (by weight) of the food purchased by the households(Fig. 3.2).

This is mainly due to the fact that enormous amounts of green water are needed to grow coffee grains (18, 292 m3/ton)., leading to the second largest amount of emdedded water of all food types, with about 450 million m3. Thus, *coffee* very significant water footprint (by food weight) by far compensates the small amount of coffee purchased (relative to the overall amount in tons of food bought).

Meat products present unsurprisingly the second largest water footprint with 8,166 m3/ton and, combined to the relatively high amount (in tons) of *meat* products bought by households, they are the food type with the largest contribution to the total embedded water in Amsterdam's household food flows, with 560 million m3 (Fig. 3.2).

It can also be noted that *tea* and *sauces and fats* have both very high-water footprints, with respectively, 8,130 m3/ton and 6, 235 m3/ton. Yet, they represent relatively small amount (by weight) of food purchased.

The embedded energy and water footprint of Amsterdam's food flows offer interesting insights from a FEW-nexus perspective into the food purchased by households. Specifically, certain food types are known to have high energy and water inputs (i.e., meat) while some other products may come as a surprise (i.e. coffee; chocolate).

These results also serve as insights for diet recommendations based on food environmental impacts and the environmental risks associated with dietary shifts. These insights will be discussed further in Chapter 8.

Furthermore, these results show the impacts of the food consumed in Amsterdam extends far beyond its physical boundaries (Heard et al. 2017). Yet, a crucial point that must be addressed is the quantification of wasted energy and water. Indeed, it represents one of the most vexing issues from a FEW-nexus perspective, because the negative costs associated with the extractive activities connecting the FEW systems to serve human society were generated for no useful end (Heard et al., 2017).

Thus, the amounts of embedded energy and water in the avoidable food waste (AFW) flows of the households are further described and analyzed.

Wasted Energy and Water in Amsterdam Food Waste Flows

The quantification of wasted embedded energy and water was performed by solely selecting the AFW flows. Concerning the UFW flows, they are, per definition, unavoidable, therefore the decision was made not to consider the embedded energy and water footprint from UFW as "wasted".

Waste Embedded Energy

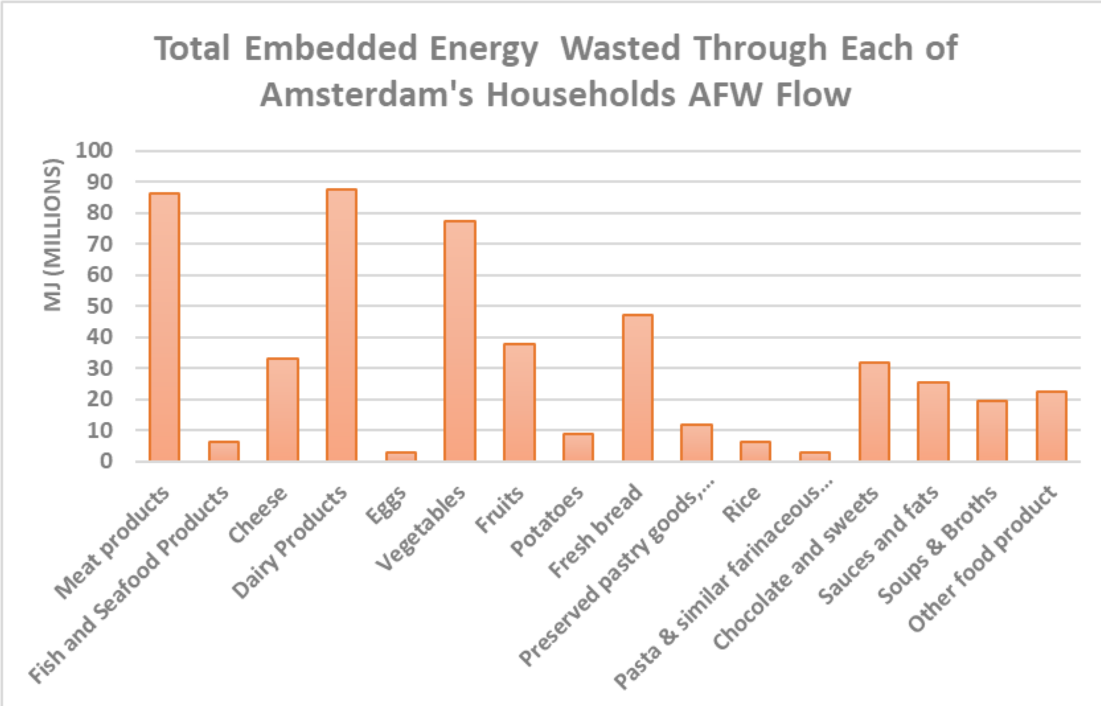


Figure 3.3: Wasted Energy from Household AFW. – The total amount in tons of AFW for each food type was multiplied by their respective energy intensity to find the total amount of wasted embedded energy.

The profile of the wasted embedded energy in the AFW flows shows some differences compared to the embedded energy in the purchased food inflows (Fig. 3.1).

Meat, *dairy*, and *vegetable* products still represent the largest contributors to the total (wasted) embedded energy, with respectively, 17%, 17%, and 15% of share of the total amount wasted (Fig. 3.4).

Therefore, relative to the first energy assessment (Fig.1), avoidable *vegetable* waste appears now almost as large as *meat* and *dairy* products in terms of wasted energy. This is explained by the fact that avoidable *vegetables* waste represents the third largest flow (by weight) of AFW produced by Amsterdam's households, twice as high as avoidable *meat* waste (Cf. Chapter 2).

Furthermore, concerning wasted *meat* products, they represent only the fifth largest AFW flow by weight. Yet as mentioned above, *meat* products have a significant embedded energy, hence their very large contribution to the overall wasted embedded energy (Fig. 3.4).

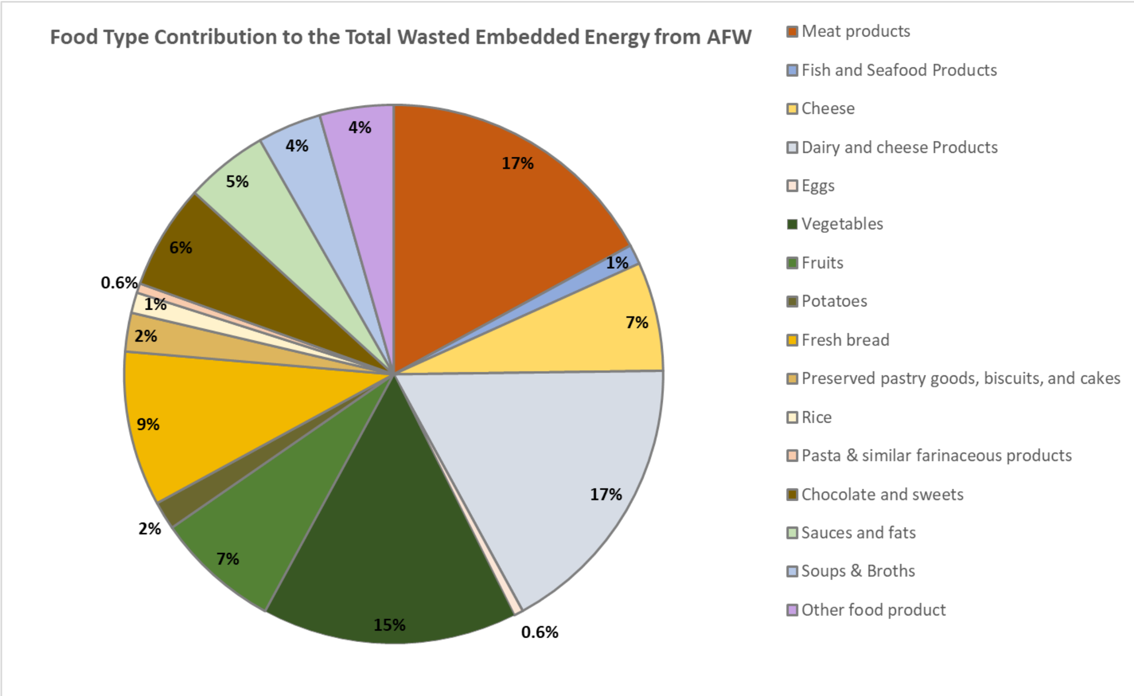


Figure 3.4: Food Type Contribution to the total Wasted Energy (in % of total MJ).

The sharp rise of *fresh bread* in the embedded energy profile is one of the key differences between the embedded energy analysis of the food inflows and the AFW outflows (Fig 3.3).

Fresh bread is the largest AFW in Amsterdam's households, with a little less than a quarter of all AFW, by weight (cf. Chapter 2). Although*, fresh bread* has a relatively very low embedded energy (6.17 MJ/kg), the sheer size in tons of this AFW flow makes *fresh bread* a large contributor to the overall wasted energy (9% contributive share to the total wasted energy, in MJ) (Fig. 3.4).

Fruits also rose significantly in the embedded energy profile due their high incidence of wastage (fourth largest) and represents now 7% of the wasted energy (Fig. 3.3; 3.4.).

Chocolate and sweets and *sauces and fats* can also be noted as relevant contributors to the overall wastage of embedded energy.

The absence of *coffee* as a contributor of the total wasted embedded energy of AFW must also be noted. As explained in Chapter 2, *coffee* AFW is very difficult to quantify due to the very high uncertainties in liquid waste data (REPAIR, 2018; Kantar Public, 2017). Thus, the wasted embedded energy of avoidable *coffee* waste (and tea) was not quantified in the overall profile. As *coffee* has a relatively high amount of embedded energy, it can be expected that avoidable coffee waste could contribute a non-neglectable share to the overall wastage of embedded energy.

Wasted Water

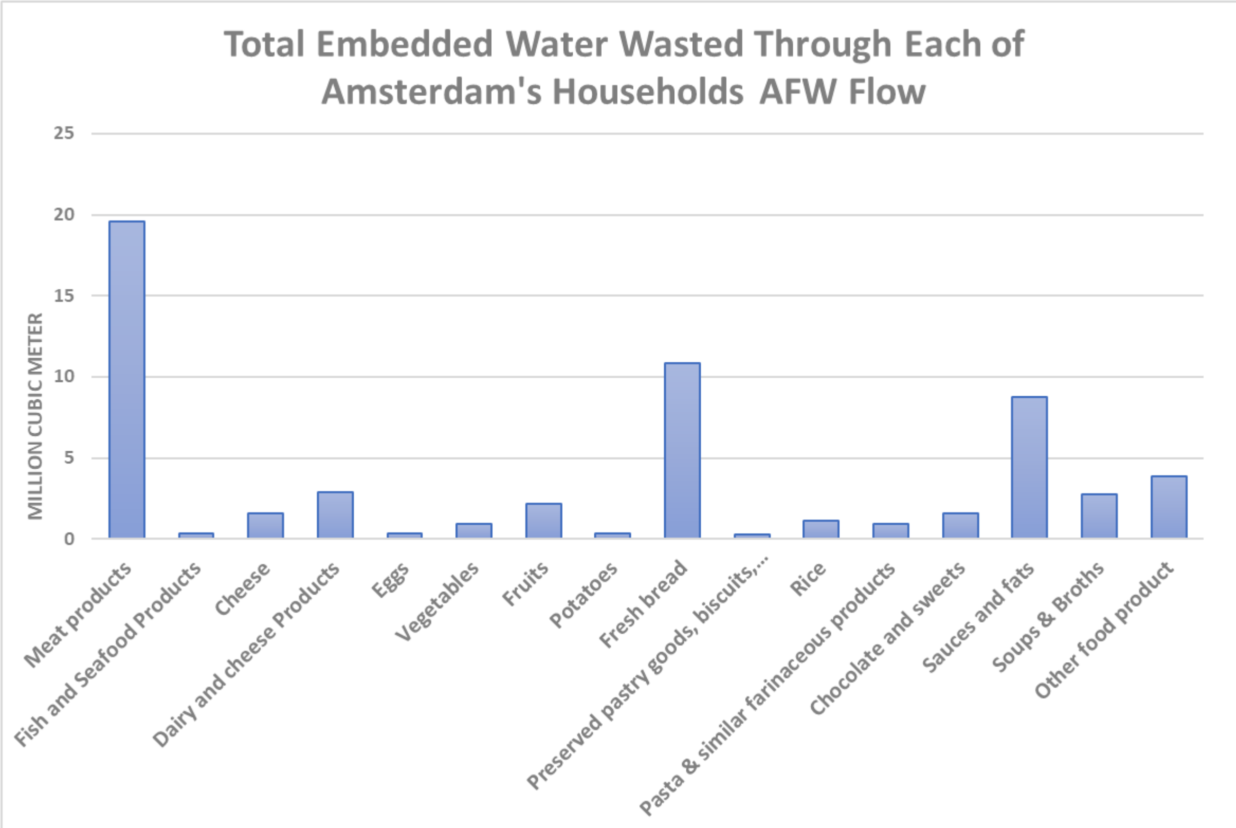


Figure 3.5 Wasted Water embedded in Amsterdam's Households AFW – The total amount in tons of AFW for each Food type was multiplied by their respective water intensity to find the total amount of wasted embedded water.

The profile of the wasted embedded water in the AFW flows shows key differences compared to the embedded water in the purchased food inflows (Fig. 3.2).

Fresh bread is again a key contributor to the overall wastage of water (Fig. 3.5; 3.6). The water footprint of *fresh bread* is relatively low (1,425 m3/ton), but the significant amounts of *bread* waste cause this food type to be the second largest (food) contributor to wasted water through Amsterdam's households AFW, with a 19% contribution (to the total wasted water, in m3) (Fig. 3.6).

Meat products are the largest contributor to the overall wasted water present in Amsterdam's AFW flows (34%, Fig 3.6). It is not surprising due to *meat* products' very large water footprint and non-neglectable amounts of avoidable wastage (fifth largest AFW flow, Cf. Chapter 2).

The high water footprint of *sauces and fats* was noted above. By looking solely at the AFW, this food type can now be observed as a significant contributor to the overall amount of water wasted due to households' production of AFW (Fig. 5).

Again, it is important to note the absence of *coffee* in the profile of the overall FW-related wasted water. As shown earlier, *coffee* has by far the largest water footprint of all food products. Thus, although not quantified in the AFW flows, *coffee* wastage, that is, drinkable coffee (as opposed to use coffee ground), discarded in the sink, could significantly influence the overall profile of the amount of wasted water in Amsterdam's households AFW flows.

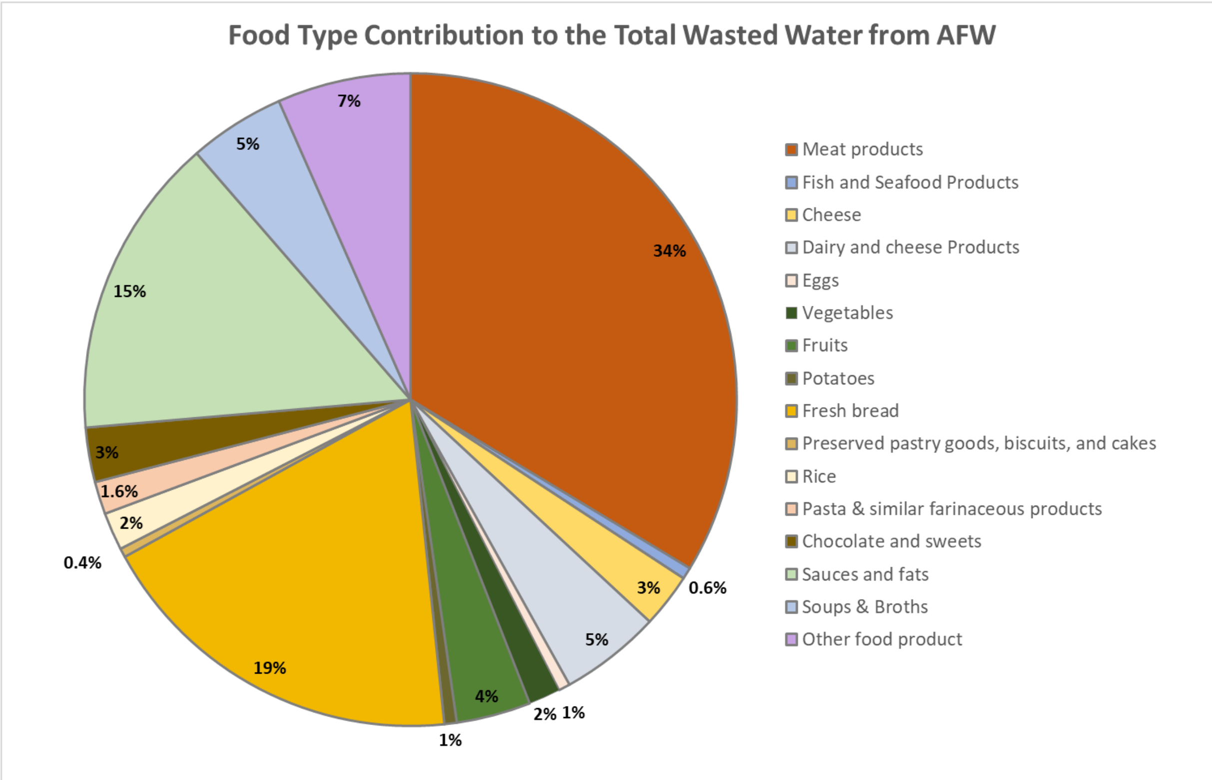


Figure 3.6: Food Type Contribution to the total Wasted Water (in % of total m3)

Putting in Perspective the Wasted Energy and Water with Households Energy and Water Uses

In the introduction of this study, it was stated that the food wasted globally represented a significant amount of wasted global energy production (1 to 1.5%) and global water use (20 to 33%) (Fox, 2013). It is interesting to verify how the overall energy and water wasted through the production of AFW flows compare relative to Amsterdam households' energy and water consumption.

According to Verheggen (2015), Amsterdam's residential sector consumed 19.3 PJ of energy in the year 2012. On the other hand, the total amount of wasted energy through the households' AFW is quantified to be 0.51 PJ (Fig 3.7). Thus, the wasted embedded energy represents about 2.6% of the total amount of energy consumed in Amsterdam's household (with 2012 as a reference year).

Contextually, electricity use represents about 17.6% of the total residential energy use in 2012 (3.4 PJ), thus the wasted energy embedded is equivalent to 15% of the total household electricity use (Verheggen, 2015).

The amount of embedded energy within the UFW was also quantified for comparison with the embedded energy in the AFW (Fig 3.7). The embedded energy within the UFW of Amsterdam amounts to 0.76 PJ.

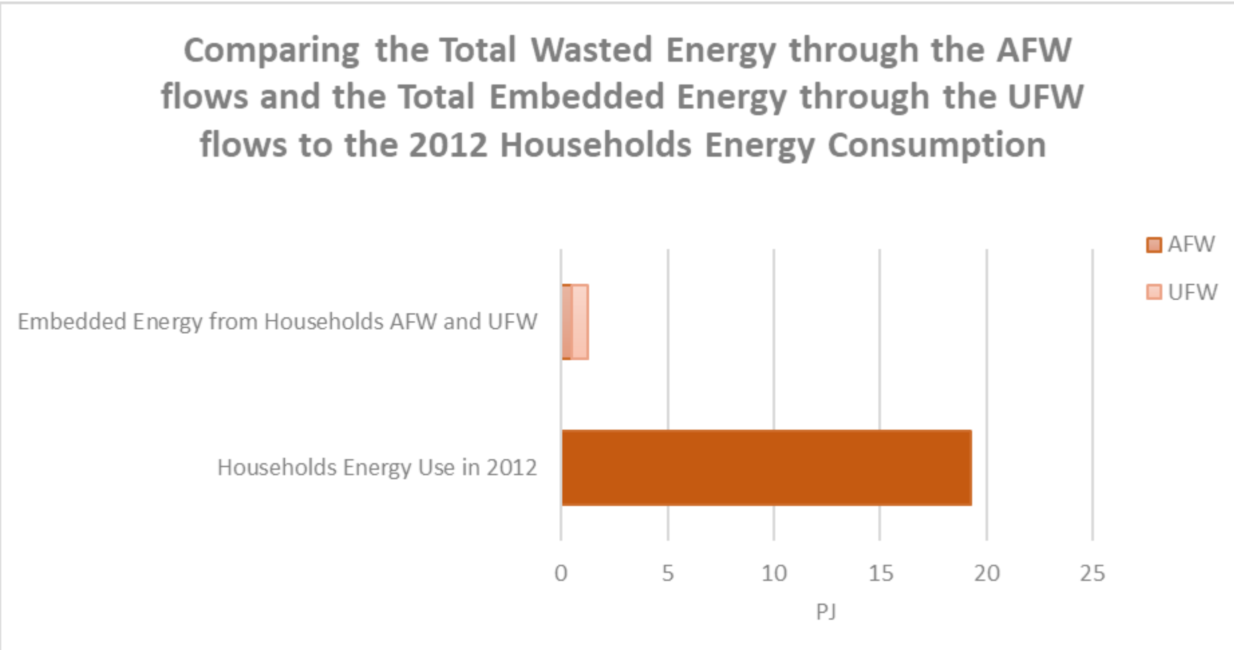


Figure 3.7: Comparison between AFW-related Wasted Energy and UFW-related Embedded Energy and Households Energy Consumption

Regarding the water use of Amsterdam's households, the average tap water use was estimated to be 133.4 liters per person per day in Amsterdam (Waternet, 2019). With 833, 420 inhabitants, the annual (365 days) total tap water consumption of Amsterdam' residents are therefore 40.6 million cubic meters (Fig. 3.8).

The total amount of wasted water from household AFW flows is quantified to be 58.3 million cubic meters. Therefore, the amount of wasted water due to entirely avoidable FW represents 1.45 times the amount of water consumed annually by these households (Fig. 3.8). This comparison enables to grasp the enormous amounts of water that are wasted when FW is generated at the household level.

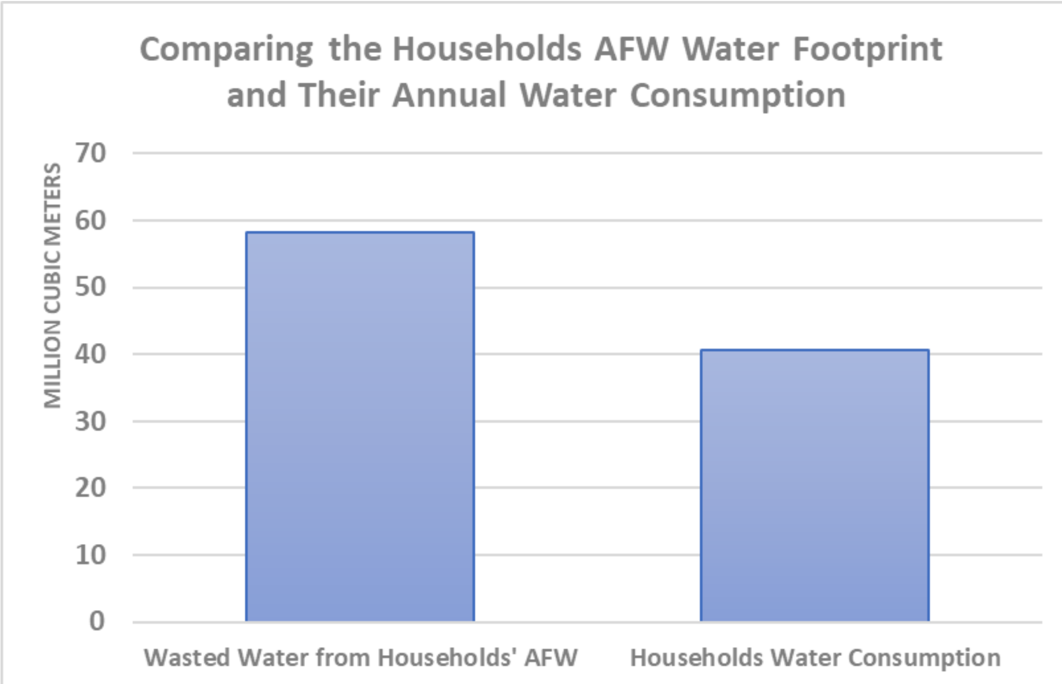


Figure 3.8: Comparison between AFW-related Wasted Water and Households Water Consumption

Conclusion

This chapter resulted in providing a new perspective into Amsterdam's FW flows, specifically considering them through their impacts on the water and energy systems that interact with the FSC.

These results show that there are few food flows contributing a significant share of the total embedded energy and water, namely *meat, dairy,* and *vegetables*, and *meat* and *coffee*, for energy and water, respectively. This has consequences for recommendations on sustainable or low-environmental impact diets (McDiarmid et al. 2016; Springmann et al. 2018). This implication will be further discussed in Chapter 8.

Furthermore, considering the amounts of energy and water wasted through FW, *meat, dairy,* and *vegetables,* and even *fresh bread* contribute to the majority of the total wasted energy, while *meat, fresh bread,* and *sauces and fats* are the major contributors to total wasted water. Consequently, these results put forwards these AFW flows that ought to be reduced in order to effectively reduce the impacts of the FW flows on the larger energy and water systems surrounding Amsterdam's food system.

For example, *meat* products appear to be a leverage point in order to reduce the burden on the water and energy systems supporting the FSCs that feed Amsterdam. A reduction in the amount of avoidable meat products wasted through, for example awareness campaigns may have, if successful, an overwhelming effect on the reduction of the total energy and water wastage through Amsterdam's FW flows. These implications will be further discussed in Chapter 8.

Last, the overall amount of wasted water from entirely avoidable FW is enormous compared to the water use by Amsterdam's households. However, considering the water context surrounding Amsterdam, which is far from water-scarcity, the significant amount of wasted water could be seen as unimportant. For regions supplying the food eaten in Amsterdam, which may be water-stressed, the resulting wastage of water may be deemed more concerning. The amount of wasted energy is also significant and should be a source of concerns though again the city, and the Netherlands in general are not energy-scarce. The importance of contextualizing water and energy use will be further discussed later on in Chapter 8.

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Chapter 4: Inventory of Food Waste Valorization & Treatment Technologies and Rescue Initiatives

Introduction

This chapter describes the main waste treatment procedures for FW taking place in Amsterdam and provide a review of the FW rescue initiatives present to date in the city.

After this reviewing, the FW rescue potential of the latter initiatives, that is their ability to recover high amount of FW, is assessed through the qualitative scoring system presented in the methodology. The scoring system is based on six criteria: price incentive, users reach, infrastructure and technology needed, ease of use, social impact, and FW awareness.

Afterwards, this chapter describe the FW valorization strategies highlighted by the state-of-the-art review of Nayak et al. (2018), namely energy valorization, value-added chemicals, bio-material, and bio-adsorbents. Last, the current waste treatment options used in Amsterdam are reviewed against these four strategic axis.

Current Food Waste Treatment and Recovery Initiatives in Amsterdam

Amsterdam Municipality does not collect separately GFT waste, therefore all FW produced by households are collected via the residual waste collection scheme. It can also be noted that businesses with a relatively low amount of residual waste (nine bags of 44L per week) is collected by the municipality (Gemeente Amsterdam, 2018). Businesses with large amounts of residual waste (above 9 bags) are required to either have a special contract with the municipality or contract a commercial waste collector (Gemeente Amsterdam, 2018).

Food Waste Treatment

AEB

Electricity and Heat

In Amsterdam, the main waste treatment plant is managed by Afval Energie Bedrijf (AEB). AEB treats about 1.4 million tons of residual waste per year. Specifically, they treat 0.6 million ton of commercial waste, 0.5 million ton of household waste, and about 0.3 million tons of waste from the UK (AEB, 2016). It produces each year about 1 million MWh of electricity and 0.6GJ of heat. This heat is used as district heating, servicing about 30,000 household in Amsterdam (AEB, 2018).

This Waste-to-Energy (WtE) plant incinerates the entirety of the residual waste it receives (household and commercial). The incineration process enables the production of electricity and heat (i.e., combined heat and power). The WtE plant also has a partnership with Waternet, the main wastewater treatment company of Amsterdam, where the biogas produced at the wastewater treatment plant is upgraded and then burned to generate heat and electricity (AEB, 2007). AEB has a similar partnership with the organic waste treatment company, Orgaworld, where their biogas is upgraded and burned to produce additional heat for the district heat network (Niessink et al., 2015). Furthermore, they burn the sludge from Waternet's wastewater treatment plant.

Material Recovery

The AEB plant recovers multiple valuable material from their residual streams, such as metal (e.g., copper, iron), plastics (during the pre-sorting) and gypsum (filtered out from the incineration residues) (AEB, 2016). The plant also recovers its bottom ash to use as an aggregate (once cleaned and purified) for the production of asphalt and for other uses in the construction industry. Furthermore, AEB is investigating with a consortium of actors the possibility to upgrades wet biomass to produce biofuels, and produce some biochemical products, like aromatics (i.e. phenols) (Amsterdam Smart City, 2015).

Biomass Power Plant

AEB is also building a biomass power plant to will use wood residuals (low-quality pruning and wood waste) from a radius of 150km around Amsterdam (AEB, 2019). The main supplier will be the landscaping industry and woodworkers (AEB, 2019). After completion, the biomass plant will burn 110,000 tons of wood residues, and producing 935 TJ of heat per year, effectively doubling the current district heat capacity of AEB.

Innovative Pilot Projects

AEB is planning to export its steam production to a nearby industrial plant, which requires a steam inflow to produce biofuels (AEB, 2018). The steam from AEB would replace the fossil fuels-powered steam currently used in their facilities. Additionally, the waste treatment plant is investigating the possibility to capture and purify the CO2 from their flue gas. The plant would ten supply the glasshouse horticulture industry with pure CO2 – a key component for plant's growth (AEB, 2019).

Other Relevant Waste Treatment Plants

For companies producing large amount of organic waste, there are several organic waste treatment companies operating in the AMA. As mentioned before, it is difficult to assess the type, the quantity, and the treatment location when it comes to companies' organic waste. Therefore, two organic waste treatment companies are highlighted as they may treat a share of the FW produced by companies within Amsterdam's municipality. Meerlanden B.V. collect organic waste from residents and companies around Amsterdam, as well as companies located within Amsterdam. From their organic waste treatment, they produce high-quality compost, biogas, condensed water, heat, and electricity (Meerlanden, 2018). Orgaworld Composting produces compost, soil improvements, biofuel, and biogas from the treatment of commercial organic waste (Orgaworld, 2018).

Food Waste Recovery Initiatives

There are several recovery initiatives taken place within Amsterdam Municipality. These initiatives were divided into two main categories: non-profit or social initiatives or for-profit or commercial initiatives. The overarching goal of these initiatives is to recover FW prior its collection by the municipal or waste collectors and its subsequent treatment.

*Non-profit & social initiative*s

The social initiatives described below are based in Amsterdam. However, some initiatives that started in Amsterdam are now present regionally (e.g., Utrecht, The Hague) or even internationally (e.g., Canada, Switzerland).

Guerilla Kitchen

Guerilla Kitchen was formed by a small group of students that started salvaging food from waste containers from markets. As it evolved, the organization set up partnerships with supermarkets and catering companies to recover their food waste. They host weekly dinners (prepared with their food donations) in the facilities of the non-profit Robin Food Kollektief.

Their dinner are pay-as-you-feel basis and all the profit is used to support their operations or provide meals for a refugee association. They also offer cooking workshops and make their recipe available to the public. They recently launched the concept of Free Supermarket, where food products salvaged from waste are made available for free for the local neighborhood. The Free Supermarket changed locations frequently across Amsterdam. The organization is entirely run by volunteers (No Waste Network, 2015; Guerrilla Kitchen Amsterdam, 2015). They aim to find a permanent location to be open to the public every day.

Robin Food Kollektief

Robin Food is an activist group holding bi-weekly vegetarian and organic community dinners prepared with food donations, and rescued FW. They also run a cooking club based on the idea of FW rescue, as well as hold events on the topic in their community space. They host the Guerrilla Kitchen organization once a week. They also performed catering operations (Robin Food, 2019).

Instock

Instock is a foundation that was established in 2014 initially with a partnership with the supermarket chain Albert Heijn, where they collected their unsold food products. The organization is now well established with three restaurants in Amsterdam, The Hague, and Utrecht. It has several other suppliers, although Albert Heijn remains their main one.

The organization also has a food sorting center where food products are made available for a reduced price. They also developed a variety of food products for sales such as craft beers (one made of wasted potatoes and one from stale bread), as well as granola.

Instock published a cooking book with hundreds of recipes, educating on how to salvage food. Finally, Instock provide educational program on food waste (Instock, 2019).

Taste Before You Waste

Taste before you Waste is a non-profit foundation started in 2012 to fight FW in Amsterdam. The organization has several partnerships with a restricted number of independent grocers. The recovered FW is distributed to charities or use to organize a bi-weekly "waste-free" dinner.

Furthermore, similarly to the Guerilla Kitchen, Taste Before You Waste holds a free weekly mini-supermarket, where rescued FW is available for free, although donations are encouraged. Every week, they select a neighborhood to distribute FW products and raise awareness on the issue in the local community.

The foundation organizes documentary screening and debate events around FW topics. They also run several FW educational workshops and may perform event catering operations (Taste Before You Waste, 2019).

BuurtBuik

Started in 2014, BuurtBuik is a non-profit organization run entirely by volunteers, who collect FW thanks to partnerships with supermarkets, grocers, and food companies. In the seven districts of Amsterdam, the organization hosts weekly free neighborhood dinners, where the local community gather to prepare dinner or simply enjoy the meals prepared with the FW recovered locally (BuurtBuik, 2019).

Oma's Soep

Oma's Soep is a non-profit organization founded in 2017 to both tackle the issues of FW and elderly loneliness. Thanks to a partnership with the supermarket chain Markt, the organization recovers vegetable and fruits that would go unsold and organize weekly cooking sessions with elderly people to create soups, in six community centers across the city. The cooking sessions enables elderly to meet new people from their age group, as well, as the younger generations. The soups created are then sold to catering companies, restaurants, cafés, and for companies' lunch and events. The sales of soup help cover the operational costs (Oma's Soep, 2019).

Dumpersterdam

Dumpersterdam is a blog no longer active, which presented how dumpster diving worked in Amsterdam. Between 2008 and 2012, a weekly dinner was organized with the FW recovered from their dumpster diving activities. Workshops were also held on the topic of FW and dumpster diving. Food catering activities were also performed. Their website shares a world map on which reported available dumpster diving sites are compiled. This dynamic map includes Amsterdam.

For Profit-Commercial Initiatives

Most for-profit recovery initiatives compiled below were not started in Amsterdam as they were first established elsewhere before expanding to the Dutch capital.

Too Good to Go

Too Good to Go was founded in 2015 in Denmark. This mobile app is available in nine countries across Europe and relies on local networks of restaurants, supermarkets, cafés, and bakeries. These food companies assemble a box of unsold food products (from the day) and sell them on the online market for a reduced price (compared to original value). The users can see on their local map where food boxes are available for sale, and after purchasing them, they must pick them up shortly before the closing time of the company. Too Good To Go takes a commission on every sale, while food companies make money from products that would be wasted otherwise (Too Good to Go, 2019).

Olio

This UK-based application enables the sharing of unsold food or food surplus in Amsterdam. Olio is an online platform founded in 2016 where neighbors and local businesses can publish about their food surplus available, by posting a picture and a description, and offer a pick-up time for interested users. All the food surplus available on the application is available for free. The company encourage food companies to publish on their platform to limit their waste (Olio, 2019).

ResQ

ResQ is an application founded in 2016 where grocery stores, restaurants, cafés can post about meals, ready-to-go snacks and full grocery bags of food about to be discarded on an online platform. On the same model as Too Good To Go, the baskets of food goods is offered at a reduced price; typically 50% less than the original value. A notable difference with Too Good To Go is that the food baskets pick-up time is immediate after the order is placed by the users (ResQ, 2019).

NoFoodWasted

NoFoodWasted is Dutch application dating from 2014. Thanks to a network of supermarkets, they advertise food products that are closed to their expiration date and offered at a discounted price by the partner supermarket. The application is present in the whole of the Netherlands, though has a limited presence in Amsterdam due to the limited local network of supermarkets present on the platform. In other word, the application sends an alert to the platform whenever food products are close to reaching their expiration date (NoFoodWasted, 2019).

Thuisafgehaald

Thuisafgehaald is an app where users can buy meals prepared by other residents in their area. Although, not specifically catered to FW, the app also makes possible for residents who have surplus food products or meals to sell it on the platform (Thuisafgehaald, 2019).

It is worthy to note the rather recent existence of all the initiatives listed above as the oldest initiative dates only from 2012 (excluding Dumpersterdam). It seems therefore that there has been a surge in awareness around the topic of FW, spurring the development of such initiatives.

Assessing the FW Prevention potential of the Recovery Initiatives

A qualitative analysis of the FW rescue initiatives was performed in this study to further understand, which rescue initiatives may have a larger potential in rescuing substantial amount of FW for human consumption. To yield this analysis, a qualitative scoring system was developed, and in which six categories were selected, namely, *users reach, price incentive infrastructure and technology needed, ease of use, social impact,* and *FW awareness.* Figure 4.1 illustrates the results of the scoring system. The grading scheme is presented in the Methodology section. The score breakdown is compiled in the Appendices (Table A5).

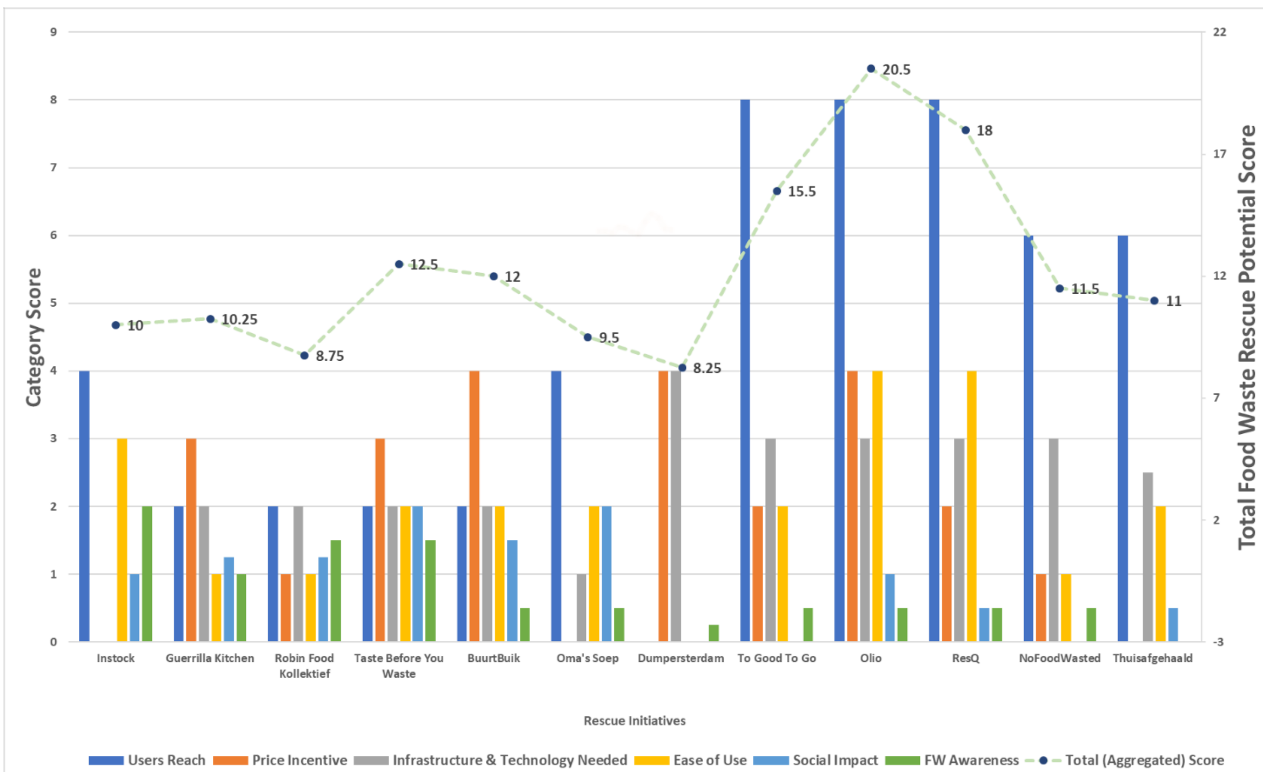

Figure 4.1: Qualitative Score of FW Rescue Potential for Each Food Rescue Initiative

From this qualitative analysis, the online application Olio, followed closely by ResQ, may have the largest potential for food rescue, this is due to a variety of factors presented below.

By and large, online application, due to their highly decentralized nature scored very well in terms of *user reach* (Fig 4.1). The ability of such online rescue initiatives to reach large numbers of users will be determinant in achieving high amounts of food waste rescue. For example, in their second year of operations, the application Too Good To Go saved two millions meals in the year 2017, and has seen a steady increase in the number of users, from 1 million users in 2016, to 7.5 in 2018 (and 10 million meals saved). With the application's growth forecasted to reach 50 million users by the end of 2020, 100 million meals could be rescued (Too Good To Go, 2019).

Conversely, social initiatives usually have a very local and restricted user reach. Although they may have a stronger social impact at the local level, their relatively small range of users limits their potential of FW rescue at a systemic (i.e. city-scale) level.

Second, among the online platforms, the price incentive of Olio is very strong, as their food rescue basket are free, more users may be attracted to this option (Fig 4.1). Price incentive is a powerful driver to incentivized FW rescue (Hooge et al. 2017; Schane et al., 2018). ResQ and Too Good To Go also offer lower prices than regular food products making these applications also very attractive. Social initiatives, such as Buurtbuik, Taste Before You Waste, and Guerilla Kitchen may also attract users due to their free or per-donation food rescue baskets and/or dinners.

Online applications performed well in terms of *infrastructure and technology needed* as very little new or existing infrastructures are required for the food rescue operations (except database centers, and regular business offices). Additionally, the strength of online applications is that they rely on smartphones and laptops that are nowadays common and readily available technologies. Indeed, the user (or penetration) rate of smartphones in the Netherlands is reaching about 93% in 2018 and is still increasing yearly (Deloitte, 2018).

Logistical constraints are recurrent issues in FW rescue, it is especially an inhibitor of FW initiatives when it falls onto FW providers (e.g., restaurant, retail stores) (Mourad, 2016). Therefore, the limited logistical constraints offered by online application is an important factor in their ability to recover large amounts of FW.

Social initiatives, on the other hand, need a minimum of a physical location (even for temporary use) to host events and store the food rescue produces. In increasingly congested cities, where space is scarce, it may difficult to find stable (i.e., readily available on the medium to long-term), affordable, and easily accessible spaces (i.e., not on the city's outskirts).

Oma's Soep and Instock score relatively low in terms of *infrastructure and technology needed* in the sense that important infrastructures are required for their operations.

Instock has the infrastructure need of a regular restaurant (three in their case) and requires a specialized food processing space to produce their beers from unsold bread and potatoes. Oma's Soep requires also a processing space to produce its soups. Instock and Oma's Soep both requires specialized and non-specialized processing equipment, therefore scoring low in this category.

A kitchen space and common cooking equipment (e.g, stove, oven, fridge) suffice for most of the other social initiatives (i.e., Buurtbuik, Guerilla Kitchen etc…), therefore these initiatives score relatively well in this category (Fig 4.1). It is interesting to note that Amsterdam social initiatives are not present on the digital space of FW rescue, which is consistent with the findings of Michellini et al. (2018).

The *ease of use* is also a crucial factor as the easier it is for both FW providers and FW receivers to connect, the more successful the initiatives will be in regard to FW rescue.

Online applications usually score relatively well in this category, although there are some nuances to uncover. For example, Olio and ResQ are very convenient to use as their food baskets can be pick-up anytime (for ResQ) or the time may be set by the user (for Olio). On the other hand, Too Good To Go makes their basket available only at the closing time of the store or restaurants, where it needs to be pick up. Olio is even more flexible for the users, because they are exactly aware of what is in the food basket they will purchase, thanks to a short description and a photo. On the other hand, ResQ and Too Good To Go only provide a generic description on what may be found in the food basket. NoFoodWasted is also limited in terms of selection as it only features the sales present in partnering stores.

Regarding social initiatives, they tend to score lower in this category as they are bound to a single location, and where diners have set menu that cannot be forecasted in advance (e.g, Buurtbuik, Robin Food). Free supermarkets from Taste Before You Waste or Guerilla Kitchen tend to change location every week, which although might lead to spreading awareness on FW in a larger area, makes it more difficult to be integrated in users' routine. Instock scores relatively well as it has an established restaurant, a website where food products may be purchase, and a clear menu.

Overall, Taste Before You Waste score relatively well compare to other social rescue initiatives. This is mainly due to its large score in the social impact category (Fig 4.1). Taste Before You Waste helps underserved communities by collecting food for charities, organize neighborhood market, as well as host events and debate. Their local social impacts are therefore large. It is difficult to assess the extent to which an initiative's social impacts influence the potential of the amount of FW rescued, but as FW is also a deeply social issue, it ought to be considered. It is interesting to note that most online applications do not score high in this category as social interactions are usually remote or extremely limited. Oma's Soep scores also high in this category due to its focus to provide inclusion and social interactions for elderly people.

FW awareness is also an important category, somewhat intangible, although metrics can be developed to assess awareness level (Qi & Roe, 2016). Instock scores high in this category as it hosts events, workshop, and produced FW educational material (e.g., FW cooking book).

Taste Before You Waste again scores very well in this category due to the screening and debate events they hold on the topic.

Most online applications provide some information on FW, yet it remains superficial, hence their lower score in this category. Similarly to the social impact category, FW awareness's influence on FW rescue potential is hard to quantify. Although, recent evidences from Denmark show that it may have an enormous influence on people and businesses' behaviors to effectively reduce FW (FUSIONS, 2018).

Overall, this scoring scheme was meant to assess which initiatives currently present in Amsterdam may have the largest impacts in terms of FW rescue. Online applications such as Olio, ResQ, and Too Good To Go may have a large impact in terms of the sheer volumes of FW rescued through their platforms. More work is needed in this topic, and limitations and new research pathways will be further discussed in the discussion section (Cf. Chapter 8).

Possible Strategies for Food Waste Valorization

There are several strategies regarding FW valorization, each of them with different consequences from a FEW nexus perspective. In this chapter four strategies will be explored, namely energy valorization, value-added chemicals, bio-materials, and bio-based adsorbent. Nayak et al. (2019) performed a state-of-the-art review exploring these four strategies. Table 4.1 presents the main outputs from these four valorization strategies.

Energy Valorization

Regarding energy valorization, FW may be transformed into an entire range of biofuels that can be used for a plethora of applications. This pathway has been extensively researched and implemented due to the rising price of fossil-based fuels and because the FW feedstock did not compete with food production but rather utilized its waste streams (Nayak et al. 2019).

Energy valorization may an important strategy for food products with high sugar content. Anaerobic digestion and fermentation have been recently favored over thermal processing (incineration, pyrolysis) due to the difficulty of the later to cope with the high moisture content of FW.

Bio-methane (from digestion) and bio-alcohol (from fermentation) are the widest applied products in this overarching strategy, although bio-hydrogen, produced through dark fermentation, has emerged as a promising new product within the energy pathway due to its high energy content, and the good performance of the production process in terms of environmental impacts (Nayak et al., 2019).

Bio-oils and bio-chars produced during incineration and pyrolysis processes are useful outputs with high energy content, although FW still represent a challenge for most current technologies.

Value-Added Chemicals

The value-added chemicals ranging from food additives to essential oils are highly valuable components for the pharmaceutical, cosmetic, and food industries (Nayak et al. 2019). Fruit and vegetables waste such as citrus peels offer a range of chemical compounds such as polyphenols, carotenoids, pectin, lipids, furfural, flavonoids, or essential oils that may extracted through a variety of processes.

In general, FW must receive certain pre-treatment such as freeze drying to preserve them from oxidation and other degradations (Nayak et al., 2019). The second step, extraction, offers a host of possible processes such as Microwave Assisted Extraction, depending on the chemical compound targeted. Finally, the last step, isolation, entails the purification of the chemical compounds previously extracted (Nayak et al. 2019).

Bio-materials

The bio-material strategy from FW valorization offer a wide range of alternative materials for industries; from polymers to fertilizers, although a large portion of applications are still produced at the lab-scale. Bioplastic such as poly-lactic acid can be made of a variety of fruit and vegetables wastes (e.g., peel, pulp), coffee, and starchy foods (Nayak et al. 2019).

Enzymes can also be extracted from FW, which has attracted a vast amount of interests for their application in industrial processes, and their ability to lower the overall environmental impacts of the latter processes. Enzymes are used in bioethanol production, juice processing, and many other applications (Nayak et al. 2019).

Citric acids constitute a staple in the food and beverage industries and may be produced using FW residues. Single-cell proteins used in animal feed can be produced from a variety of substrate from FW. Last, bio-fertilizers (through composting) is a well-established biomaterial that may be produced from different FW sources (Nayak et al. 2019).

Bio-adsorbent

Bio-adsorbent has emerged as a new pathway for the production and use low-costs adsorbents to treat wastewaters (Nayak et al. 2019). Bio-adsorbent made from FW such as banana peels, may be used to filter out toxic compounds such as heavy metals from wastewater (Nayak et al., 2019).

Table 4.1:General FW Valorization Strategies	
Energy Valorization Biofuels: bio-alcohol, bio-hydrogen, bio-methane, Bio-chars Biogas	Value-Added Chemicals Additives, proteins, sugars, pectin, flavonoids, phenols, essential oils, furfural
Bio-Materials Bio-polymers Enzymes Organic Acids Single-cell Protein (Feed) Bio-Fertilizers	Bio-Based Adsorbents Wastewater Char Adsorbents

In the case of Amsterdam, the energy valorization strategy has been put forwards with AEB, its WtE incineration plant. As mentioned previously, most of the FW is currently incinerated with the rest of the residual waste streams from both residents and businesses. Biogas extraction is also taking place at the plant, therefore the AEB is deemed to have accomplished a substantial effort in the direction of energy valorization, though not targeting FW specifically.

Furthermore, the AEB-pilot, which investigates the potential of extracting phenols from the biomass received at the plant represents a small step in the direction of the value-added chemicals strategy.

Meerlanden B.V. through its biomass plants produces high-grade compost, soil improvement, as well as biogas. The organization is therefore oriented toward both exploiting the energy valorization and bio-material strategies. Similarly, Orgaworld is also producing bio-fertilizers and energy (through biogas extraction) and is therefore positioned along these two axes.

There is no current project performed in the direction of the bio-char valorization strategy in Amsterdam. Table 4.2 provides a summary for Amsterdam current strategies and outputs. Again, the current strategies in Amsterdam stem from exploiting some organic waste streams, and are not specifically targeting FW.

Table 4.2: FW Valorization Strategies Present in Amsterdam	
Energy Valorization Biogas- AEB; Meerlanden B.V.; Orgaworld	Value-Added Chemicals Phenols – AEB pilot
Bio-Materials Bio-Fertilizer – Meerlanden B.V.; Orgaworld	Bio-based Adsorbents *No project*

In the next chapter, technologies present in the four valorization strategies are investigated from a FEW-nexus perspective.

Conclusion

This chapter presented the current FW treatment practices taking place in the Dutch city. At the moment, the treatment of FW from households is indissociable from the treatment (i.e. incineration) of residual food waste. However, the WtE plant AEB, and organic waste companies such as Orgaworld have shown great interests in developing new resources from Amsterdam's waste streams, notably with their biogas and compost production from a variety of organic streams.

Consequently, this analysis highlights the current capabilities present within Amsterdam to treat and valorize its FW streams. The city is well-positioned to pursue its efforts along the energy valorization and bio-materials strategies, and these waste treatment companies could be strategic partners for the city's future FW valorization strategy. On the other hand, the value-added chemical strategic orientation is still at its infancy in the city. Yet, the AEB pilot program translates a growing interest in using FW as a bio-feedstock for chemical processes.

Additionally, the constellation of social and commercial initiatives rescuing FW uncovered in this chapter is striking by its size and variety. The role of these initiatives is multiple; from potentially recovering important quantities of FW, to raising awareness and educating local residents about the issue. These two stakeholder groups could play an important role at the grass-root level.

A main take-away from these results is that although a qualitative overview of this rescue organization is an important first step in their analysis, there is a need to quantitatively assess the recovery impacts of these initiatives. To date, it is difficult to assess their overall contribution to limit the size of FW flows from wholesale, retails, restaurants, and food services. These implications and future research opportunities will be further discussed in Chapter 8.

Chapter 5: Energy and Water Inputs and Product Outputs of Food Waste Valorization Technologies

Introduction

If FW prevention should always be the primary goal for AFW, valorization should be always be sought for UFW. This chapter is investigating the energy and water requirement in the four FW valorization strategies presented in Chapter 4, namely energy valorization, value-added chemicals, bio-material, and bio-adsorbent.

Within the energy valorization strategy, the technologies and techniques investigated for their energy and water requirements are anaerobic digestion, biofuels production, pyrolysis and incineration (both mixed waste and biowaste). The value-added chemical strategy is analyzed through the case of (hydroxymethyl)furfural (HMF) and pectin production from FW. The bio-material strategy is constituted of the technologies producing compost, biopolymer, enzyme, and the bioconversion process that produce both compost and protein through Black Soldier Flies (BSF) larvae digestion. Last, bio-adsorbent, the fourth valorization strategy was also included in this water and energy analysis. Overall, 12 technologies are reviewed for their energy and water requirements.

From a FEW nexus perspective, it is important to understand the energy and water intensities of FW treatment technologies in order to avoid shifting the burden onto the water and energy systems (Kibler et al. 2018). This chapter also directly aims to bridge the gap identified by Kibler et al. (2018), which suggested a lack of understanding of the interactions and dynamics between FW treatment systems and the energy and water systems. Furthermore, their study pointed out that there is no general overview of the energy and water requirement to treat FW. This study suggested the latter point as a research priority in FW studies. This chapter attempts to address this priority.

Determining the energy and water requirements of these technologies can help inform municipalities of the most energy and water-efficient technologies to treat their FW. This is key information if they are located in water or energy-scarce environment or aimed to reduce their water and/or energy consumption. In the case of Amsterdam, the city of Amsterdam has ambitious targets to reduce the energy consumed by its residents, and also aims to increase its renewable energy production (Hoek et al. 2015).

The first section of this chapter focuses on the energy inputs of the 12 technologies relative to a ton of FW treated by these technologies. The second section focuses on the water inputs of each of the 12 technologies relative to a ton of FW treated by these technologies. The third section focuses on the economic values of the outputs produced by these technologies.

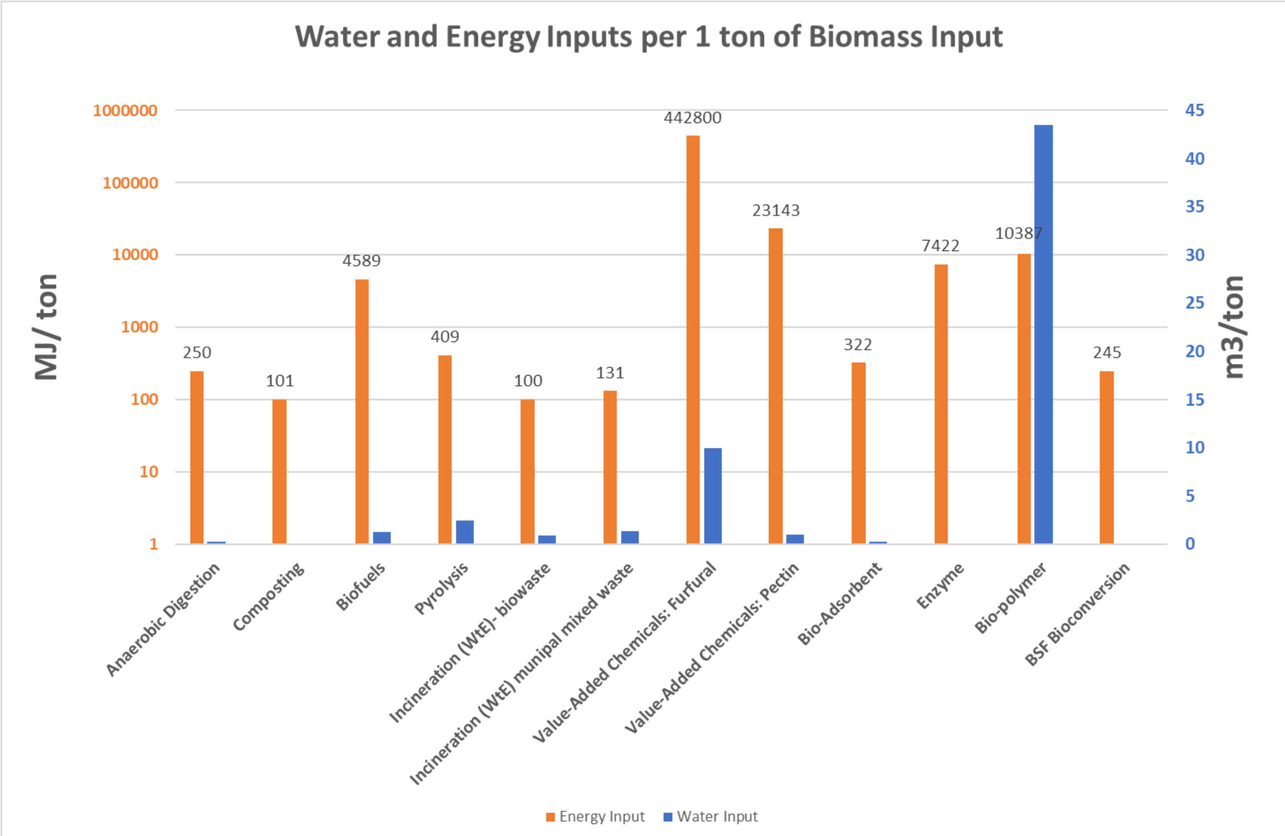

Figure 5.1: The energy and water required to treat 1 ton of biomass for 12 different technologies

A first appraisal of the results reveals that furfural extraction, from the value-added chemicals strategy uses by far the highest amount of energy per ton of FW treated, followed by pectin extraction, also part of the value-added chemicals strategies. Composting, incineration, anaerobic digestion, and BSF bioconversion use the lowest amounts of energy (Fig. 5.1).

Furthermore, the figure reveals that bio-polymer production, from the bio-material strategy uses by far the highest amount of water per ton of FW treated, followed distantly by furfural extraction. Composting, enzyme, anaerobic digestion, and BSF bioconversion use the lowest amounts of water by a substantial margin (Fig. 5.1). These findings are based on input-level.

Energy Requirement for 12 FW Valorization Technologies

Figure 5.1 illustrates the results of the energy inputs required to treat one ton of biomass of FW. Note that the left-handed Y-axis uses a log10 logarithmic scale.

In order to be able to compare the different treatment technologies that produce a variety of by-product streams (e.g., energy, materials, chemicals), the comparison at the input level was chosen as the most appropriate way to compare their water and energy intensities. In other words, the energy and water process inputs to treat one ton of FW were used as a way to analyze them from a FEW perspective.

The first striking feature of the histogram is the enormous amount of energy required during the extraction of value-added chemicals from FW. Indeed, the furfural extraction uses 442,800 MJ of energy for every ton of FW valorized (Fig 5.1). This is up to three orders of magnitude higher than the energy inputs for anaerobic digestion (AD), incineration or pyrolysis, to cite only those.

However, these results must be put into perspective in the light of the data source used. Indeed, the estimation of energy inputs were based on the LCA study performed by Lam et al. (2018) focused on (hydroxymethyl)furfural extraction from a mixture of FW products. This study was performed at a lab-scale, therefore there are relatively high uncertainties in terms of process inputs as it is unclear how lab-scale processes may translate into large-scale industrial plants.

Nonetheless, these results do bring attention to the question of assessing the energy intensity of new bio-processes that have been increasingly put forward as new sources of materials and energy. As Bello et al. (2019) emphasized in their energy footprint review of biorefineries, it is commonly thought that bio-refineries have lower impacts from an environmental perspective. Yet certain processes require significant amounts of energy (Bello, 2019).

Bioplastics is also notably an energy intensive option, with 10,387 MJ for every ton of FW transformed into bioplastic (Fig 5.1). Steam requirements are especially high during the production processes (Harding et al. 2017). Nonetheless, when compared to other fossil-fuels based plastics such as high-density polyethylene, the bioplastics performed rather well in terms of energy use during production, and over its entire life-cycle (Harding et al. 2017).

Enzyme production, which can be produced using potato wastes requires a substantial amount of energy (7422 MJ/tonFW), especially due to high heating requirements during the fermentation process (Dunn et al. 2012) (Fig 5.1). Conversely, enzyme use in industrial processes has led to energy and water savings (Nielsen et al. 2007; 2009).

Additionally, biofuels represent another rather energy-intensive valorization option, although fuels production are usually energy-intensive processes.

Last, anaerobic digestion, composting, pyrolysis, incineration, bio-adsorbent, BSF bioconversion present the same order of magnitude regarding energy use, with composting having the lowest energy input intensity (101 MJ/ton of FW treated), along with incineration of biowaste (Fig 5.1). Considering the incineration options, it is likely that these figures may be underestimated due to the high moisture content of FW. Indeed, the high moisture content of FW requires much more energy to be incinerated (due to the required evaporation of water), as explained by Nayak et al. (2019).

Water Requirements for 12 FW Valorization Technologies

Figure 5.1 also illustrates the different water input requirements (right-handed axis). As it can be observed, the water inputs of the bioplastic production process are very high compared to the rest of the technologies assessed, with 43.5m3 of water used for every ton of FW treated. Plastics are usually a relatively water-intensive material to produce (Water footprint Network, 2009).

The production of furfural is also a rather water-intensive option, with about 10m3 of water used for every ton of FW valorized.

Pyrolysis appears as the most water intensive solution *among the* five energy-valorization technologies (e.g., anaerobic digestion, biofuel, and the two incineration processes), with a water use of 2.48m3/ton of FW treated. There seems to be little difference between the incineration of biomass and the incineration of municipal mixed waste (0.9-1.4 m3/tonFW) (Fig. 5.1). Anaerobic digestion and bio-adsorbent emerge as low-water solutions, with similar water requirements (~0.22m3/tonFW). The process of creating protein feed and compost thanks to BSF bioconversion seems to be one of the least water demanding options (0.061m3/ton FW). It is therefore an interesting solution to explore further.

Figure 5.1 shows that the composting option does not require water, yet after briefly reviewing industrial-scale composting literature, water inputs may indeed be needed. During composting, the watering of the organic matter may occur in order for the compost to keep its moisture content between 35% and 60% (ACT Government, 2010). Thus, depending on the environment temperature, water inputs for composting may rather be substantial (e.g., hot and dry weather). In the context of Amsterdam, however, the water inputs should be minimal considering the local temperate climate.

Regarding enzyme production, the ecoinvent 3.5 life cycle inventory did not list water as input in the production process. However, according to Nielsen et al. (2007), enzyme production does require water, especially during the dilution process of the feedstock, prior to fermentation. The freshwater use during the production of enzyme can therefore not be neglected (Nielsen et al. 2009). No data was available clearly stating the water inputs for the processes pertaining to enzyme production. Thus, more research ought to be performed on the subject.

Outputs and their Economic Value for the 12 FW Valorization Technologies

Physical Outputs for each Technology

The table below (5.1) presents the main energy, material, and chemical outputs of the 12 technologies assessed in this chapter. These numbers stem from the studies used to quantify the energy and water inputs of these technologies. Note that the bio-adsorbent has been integrated within the bio-material cluster. It was deemed appropriate as the bio-char are used as a material to filter out toxic compounds in wastewater treatment plant. In addition, the BSF bioconversion is considered to be part of a new distinct cluster, namely, Feed. This

Feed cluster is in line with the bio-based *Value Pyramid* presented in this next chapter. These clusters will now be referred to throughout Chapter 5 and 6.

Table 5.1: Summary of Product Outputs for the 12 Technologies Valorizing 1 ton of Food Waste

Technology	**Energy Outputs** (includes all energy types) MJ/tonFW	**Material Outputs** (kg/tonFW) Economic Value	No Economic Value	**Chemical Outputs** (kg/tonFW)	**Strategic Cluster**
Anaerobic Digestion	4326	0	620 (digestate)	0	Energy
Biofuel	7879*	0*	0	0	Energy
Pyrolysis	9187**	0**	0	0	Energy
Incineration (WtE)-biowaste	1414	0	0	0	Energy
Incineration (WtE) municipal mixed waste	4240	0	0	0	Energy
Value-Added Chemicals: Furfural	0	0	0	176 (HMF)	Chemicals
Value-Added Chemicals: pectin	0	0	0	108 (pectin)	Chemicals
Bio-Adsorbent	0	150 (bio-char)	0	0	Bio-material
Bio-material (polymer)	0	552 (PHB)	0	0	Bio-material
Composting	0	500 (compost)***	0	0	Bio-material
Enzyme	0	213	0	0	Bio-material
BSF Bioconversion	0	30 (larvae feed) ; 335 (compost)***	0	0	Feed

** or 294 kg of bio-ethanol (26.8 MJ/kg).*

*** electricity and syngas production- plus includes 240kg of bio-char (29.02 MJ/kg) and 40kg of woody tar (28.44 MJ/kg).*

**** High grade compost has low economic value but does generate revenues for specialized producers (e.g., Protix, Orgaworld)*

First, pyrolysis produces the largest amounts of energy outputs, with 9187 MJ/ton. This technology produces a variety of energy products, namely electricity, syngas, bio-char, and woody tar (Yang et al., 2018). Bio-char has a high energy content (29.02 MJ/kg), and accounts for most of the overall energy production (~75%).

Yet, as Nayak et al. (2019) warned in their study pyrolysis processes rarely uses a pure FW feedstock due to its high-moisture content; and substantial pre-treatment processes may take place to allow FW to be used a feedstock, therefore using more water and energy, and reducing the overall energy outputs.

Biofuels production presents the second highest energy output with 7879MJ per ton of FW valorized. Yet, as it was shown in Figure. 5.1, biofuels production requires a substantial amount of energy (4589MJ/tonFW), the highest by far of the five technologies from the energy cluster.

An anaerobic digestion plant treating one ton of FW may produce about 4326 MJ of energy (heat and electricity), which is the third largest amount of the technologies in the energy cluster.

The incineration of mixed-municipal waste produces the fourth largest amount of energy (4240MJ/tonFW), although the FW is diluted in the rest of the residual waste stream, therefore the valorization aspect of FW is minimal. Furthermore, as mentioned before, incineration and waste-to-energy processes only using FW-based feedstocks would require substantial amounts of energy due to the high moisture content of the feedstock, which may offset the energy recovered (Nayak et al. 2019).

Regarding the material outputs, 1 tons of FW valorized into PHB bio-plastics produces about 552 kg of bio-material. It can be noted that food products with high sugar and starch contents would be more favorable as a feedstock for bio-plastics (Harding et al., 2007).

Additionally, about 150 kg of bio-adsorbing bio-chars could be produced by treating 1 ton of FW, which could be used in wastewater treatment plants as a low-cost toxic filter (De Gisi et al., 2016).

Furthermore enzyme production from FW may produce around 200 kg of this widely used bio-material. BSF bioconversion may produce about 30 kg of dried BSF larvae, while still producing 335kg of high-grade composts from the BSF excreta (Mondello et al., 2018). Finally, composting may generate about 500kg of high-grade compost (and related soil improvements) from the treatment of 1 ton of FW.

For the chemical outputs (i.e., HMF, pectin), the pre-treatment, extraction, and isolation steps may yield about 176 kg of HMF and 108 kg of pectin from a variety of FW products. Note that these figures were scaled-up from lab-scale chemical extraction studies. Therefore, these figures present a certain level of uncertainties, further discussed in Chapter 8.

Economic Outputs for each Technology

The outputs produced by these technologies have various economic values as presented in the Methodology (Cf. Table M7). The economic output in euros for each technology was therefore quantified by multiplying outputs' prices with the total amounts of outputs produced for each ton of FW valorized. Figure 5.2 and 5.3 help compare the economic outputs and the energy and water used to valorize 1 ton of FW. Note that the x and y-axis for Figure 5.2 and 5.3 are represented with a log2 scale for visualization purposes.

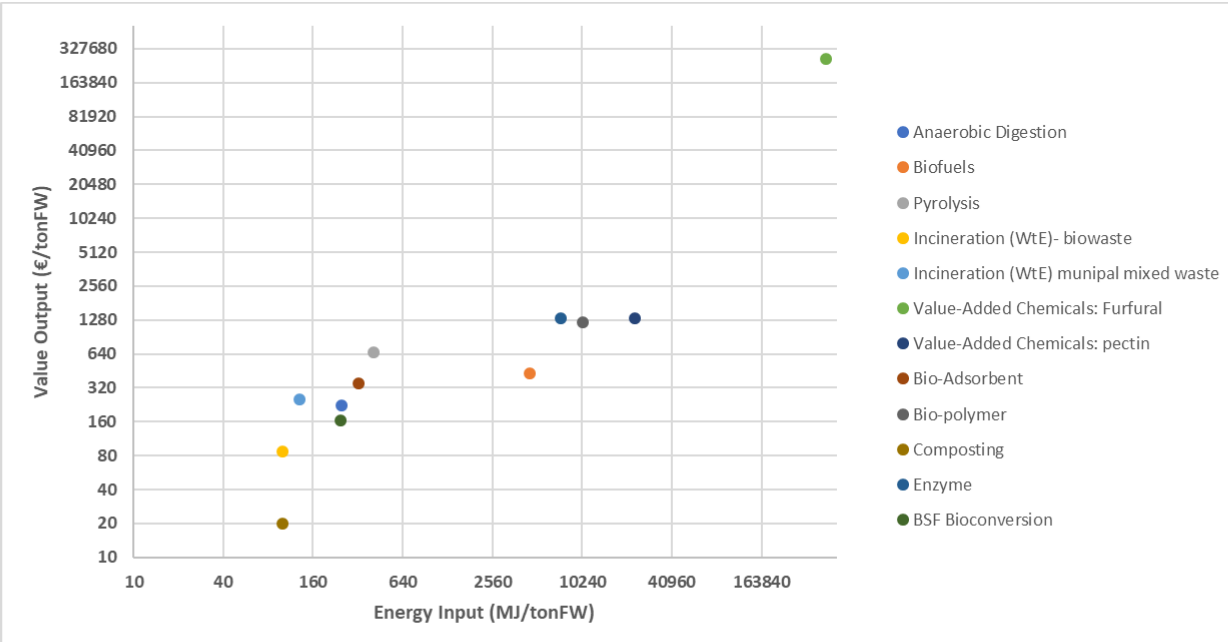

Figure 5.2: Economic Outputs over the Energy Inputs for 1 ton of FW Valorized by each Technology

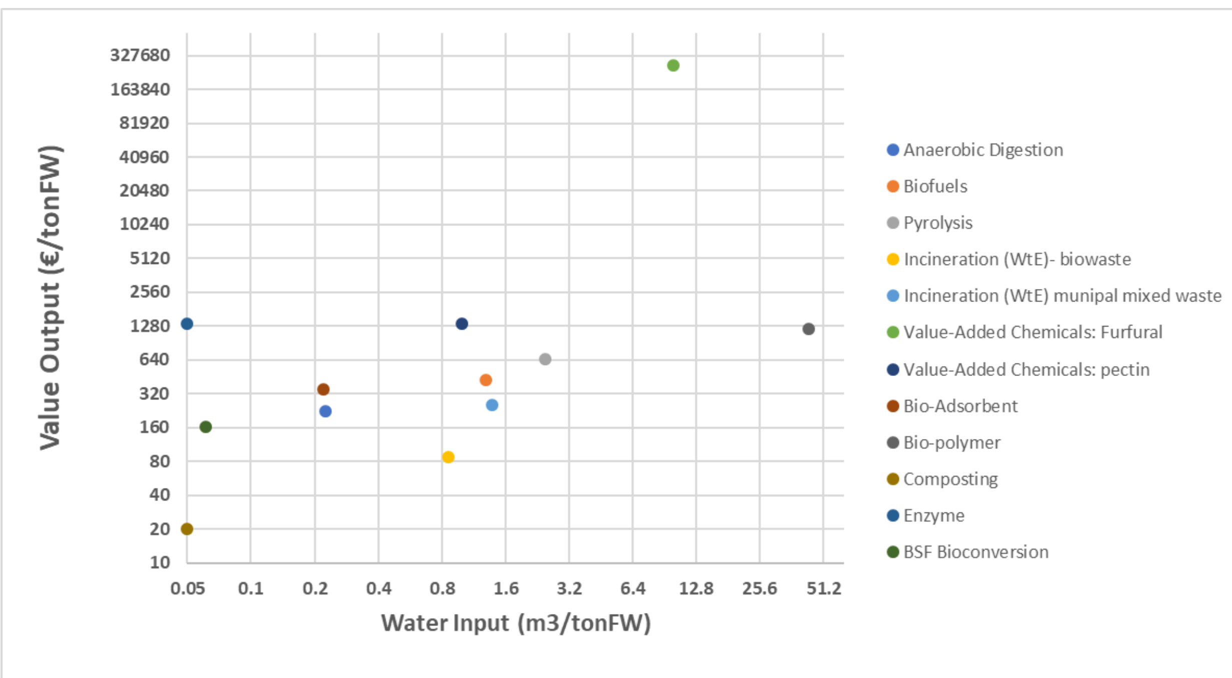

Figure 5.3: Economic Outputs over the Water Inputs for 1 ton of FW Valorized by each Technology

First, it can be noted that there is a somewhat visible trend where higher energy and water inputs are related to higher value outputs. There is a strong correlation (r=0.99) between the economic value produced and the energy inputs used during the valorization of 1 ton of FW.

On the other hand, there is almost no correlation between the economic outputs and the water inputs to valorize the same amount of FW (r=0.12). By and large, these correlations must be observed *very conservatively* considering the nature and the simplicity of the economic assessment performed in this chapter. A figure illustrating the economic output for each technology is compiled in the Appendices (Fig. A4).

The economic output of furfural (HMF) production is extremely high relative to the 11 other technologies (267 520€/tonFW), however it is related to similar extremes regarding its energy use (442 800 MJ/tonFW), and to a lesser extent, its water use (Fig. 5.2; 5.3).

Pectin, enzyme and bioplastic productions have similar economic outputs (~1200-1300€/tonFW), although there are some variations in terms of energy and water inputs. Enzyme and bioplastics have similar energy inputs, while pectin is notably higher in terms of energy inputs (23 143 MJ/ton FW). Pectin extraction therefore requires high energy inputs but provides moderate economic returns compared to enzyme and bioplastic productions, with similar returns but much lower energy inputs.

Additionally, the difference is striking in terms of water inputs. Enzyme production does not use any water and therefore appears as the most water-efficient technology from an economic perspective. Though, as mentioned above, enzyme production may use in practice a substantial amount of water during the dilution of the feedstock (Nielsen et al., 2009).

Bioplastic production has high water requirements to valorize 1 ton of FW, making the economic outputs relatively low compared to other technologies (i.e. enzyme and pectin) from a strictly water-consumption perspective (Fig. 5.2; 5.3).

Biofuel production presents relatively high energy inputs (4589 MJ/tonFW) compared to its economic output (429€/tonFW) and relative to other technologies (e.g., pyrolysis; mixed waste incineration; bio-adsorbent) with similar economic outputs (~250-650€/tonFW), but lower energy inputs (100-409MJ/tonFW) (Fig. 5.2; 5.3). On the other hand, biofuel production, pyrolysis, and mixed waste incineration present similar economic-output-to-water-input relationships, with their water inputs ranging from 1.3 to 2.5 m3/tonFW.

Anaerobic digestion and BSF bioconversion have very similar economic output-to-energy-input relationships. In fact, anaerobic digestion appears to have slightly higher economic outputs (224€/ton FW) compared to BSF bioconversion (163€/tonFW), but both have very similar energy requirements.

On the other hand, alike enzyme production, BSF bioconversion appears as very advantageous in terms of economic outputs per water "invested" to valorize FW. Therefore, this technology uses less water than anaerobic digestion, and substantially less than biowaste (with substantially lower economic outputs) and mixed waste incineration.

Additionally, bio-adsorbent production holds a very similar picture than anaerobic digestion. The former has slightly higher economic outputs (351€ vs 224€/tonFW) but both have similar water (0.22-0.225 m3/ton) and comparable energy inputs (322 and 250MJ/tonFW, respectively) (Fig. 5.2; 5.3).

Finally, compost has low economic outputs, which is visibly related to low energy and water inputs (Fig. 5.2; 5.3).

Next, Figure 5.4 illustrates the economic outputs of each technologies over the energy and water input costs. To calculate the costs, the energy and water inputs for each technology was therefore multiplied with the energy (electricity and heat) costs and water costs for each ton of FW valorized (see Table A6, in the Appendices for the cost breakdown). As mentioned in the Methodology, the cost assessment considers solely the direct energy and water inputs and therefore represent a very simplified cost structure for each of the technologies assessed. Note that a log2 scale was used for the representation of the y and x-axis.

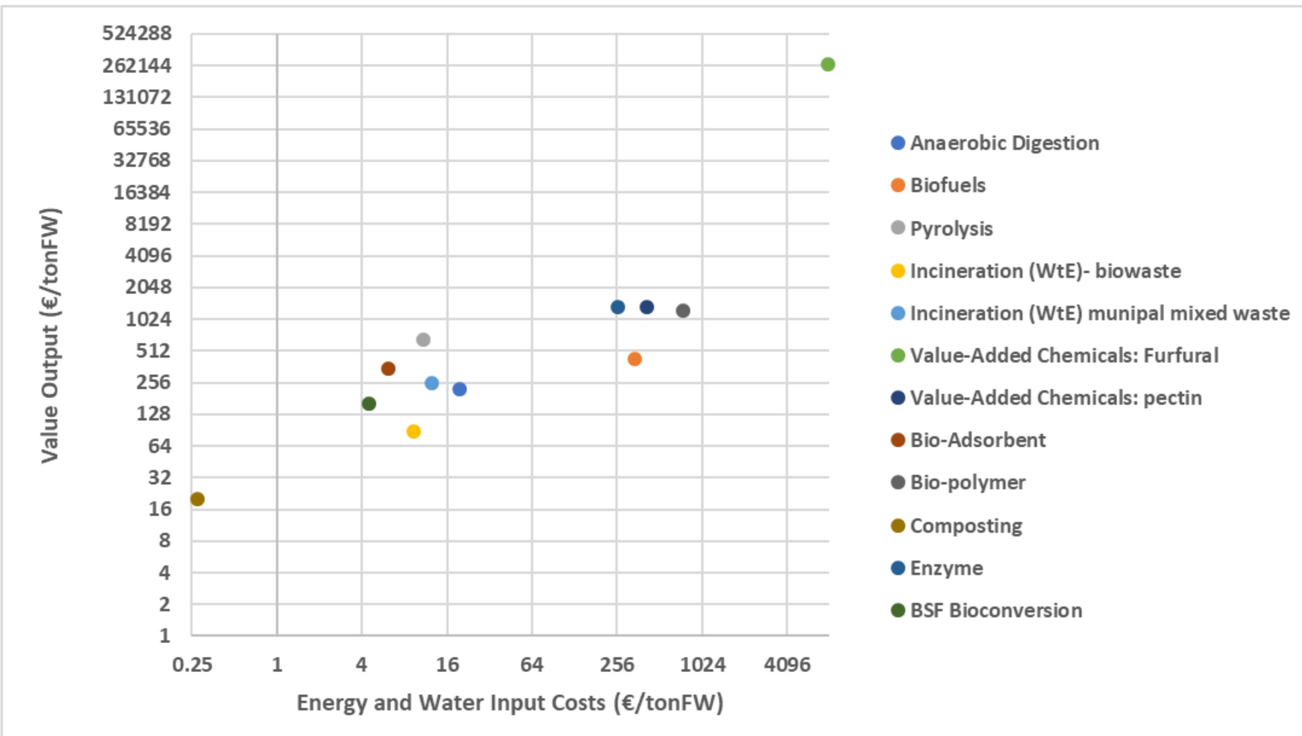

Figure 5.4: Economic Outputs over the Energy and Water Input Costs for 1 ton of FW Valorized by each Technology

First, there is again a strong positive correlation between the economic outputs and the combined direct energy and water input costs. This may be explained by the fact that most of the total costs of the energy and water inputs is incurred due to the energy inputs. The water input costs represent, in average, only 6.6% of the combined costs for the 12 technologies assessed.

HMF production has the highest input costs (8009€/tonFW) due to its energy-intensive extraction processes (Fig. 5.4).

Enzyme, pectin, and bioplastic products have similar relationships, mostly due to their economic outputs. Although, it is interesting to note that while pectin extraction requires about the double amount of total energy than bioplastic production (Fig. 5.1; 5.2), the latter faces higher energy input costs (694€/tonFW) than the former (418€/tonFW). It is due to the bioplastic production's high heating requirements and the higher costs of heating compared to electricity (Fig. 5.4).

Due to its high energy requirements, biofuel production has very high input costs (341€/tonFW) relative to technologies with similar economic outputs, such as pyrolysis, bio-adsorbent, or even mixed-waste incineration (6-12€/tonFW input costs) (Fig. 5.4).

Beside biofuel, anaerobic digestion has slighter higher input costs (19.8€/tonFW) than the rest of the technologies from the energy cluster, namely pyrolysis, and the two incineration processes (9-12€/tonFW). This is due to the higher heating requirements for this technology (242MJ vs 100, 131 and 0 MJ of heat for biowaste incineration, mixed waste incineration, and pyrolysis, respectively).

BSF bioconversion appears as an interesting option with low input costs (4.5€/tonFW) related to moderate economic outputs. For example, this technology has half of the input costs of biowaste incineration (9.2€/tonFW) but almost double of the economic outputs (163 vs. 87€/tonFW).

Finally, compost has very low inputs requirements, and therefore low inputs costs (0.28€/tonFW) (Fig. 5.4).

Conclusion

This chapter reveals important insights into the water and energy requirements of FW treatment and valorization technologies, as well as the production of useful outputs from the valorization of FW.

First, this chapter is key to help answer the four questions laid out by Kibler et al. (2018), namely, how much water and energy is required to managed FW; how do FW treatment technologies vary in terms of their water and energy intensity; how do water and energy inputs at the FW management stage compared to the energy and water used at the production stage; how grey water production during FW management be compared to blue (i.e. irrigation) and green (evapotranspiration) water use at the production stage.

The two first questions were partly answered throughout this chapter.

The water use of FW treatment technologies varies from close to 0m3/tonFW (composting) to 43.5 m3/tonFW (bio-polymer), with an average of 6m3/tonFW but a median of 1.145m3/ton of FW. The average is severely skewed due to the outlying water consumption of biopolymer production.

The energy use of the 12 technologies varies from 100MJ/tonFW (Incineration/ Composting) to 442 800 MJ/tonFW (furfural extraction). The average and median energy use are, respectively, 40 825 MJ and 366 MJ per ton of FW. The very high energy intensities of furfural and pectin extraction extremely skew the average.

Regarding Kibler et al.'s two last questions a rapid comparison was made between the weighted average water used for the production of all food types purchased by households and the water used by each valorizing technology. It was concluded that the water used during FW valorization processes were marginal compared to water inputs used during the production of food products, with the average water used during FW valorization representing less than 0.30% of the total water used during the production (using the weighted average as a proxy). The amounts of grey water produced through these 12 technologies is also minimal compared to the blue and green water consumed during the production stage.

Overall, the value-added chemical strategy seems the most energy intensive, while bio-polymer (bio-material strategy) seems the most water-intensive process. Composting, anaerobic digestion, BSF bioconversion, and bio-adsorbent seem to be both the least energy and water intensive options.

In addition, there seems to be a positive correlation between the economic value of the technologies' outputs valorizing 1 ton of FW and the energy inputs required for their valorization processes. This correlation is absent in the case of the water inputs. Furfural extraction presents the highest economic output per ton of FW while compost presents the lowest.

Last, through this chapter, this study finds an important gap in the literature on the energy and water requirements (and more generally of the environmental impacts) of the production of value-added chemicals. The energy and water use values for both value-added chemicals are based on lab-scale experiments, which may not be representative of large-scale industrial processes. The literature on this topic remains very scattered and lacks substance and cohesion. Additionally, it is unclear how much water is required during the production process of enzyme. These points will be further explored in Chapter 8.

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Chapter 6 – A New Food Waste Management and Valorization Framework

Introduction

In this chapter, two frameworks are reviewed in the light of FW valorization overarching strategy, namely the namely the Value Pyramid (VP) bio-based economy and the FW Management hierarchy (FWMH). Based on this, a new framework is developed to guide the strategy on FW-valorization from a FEW-perspective. The new framework is used to illustrate the possible strategies for the case of Amsterdam.

Value Pyramid- Bio-based Economy.

The *Value Pyramid* model was developed by the Bio-Based Economy society located in the Netherlands. The pyramid represents the valorization hierarchical strategy from the highest value-added application to the lowest from an economic perspective. The model illustrates that an increase in volume of biomass decreases the economic value derived from its valorization.

The highest value-added valorization option is constituted of products catered to the health and life style industries. More precisely, pharmaceutical and fine chemical components extracted from biomass have high economic values. The top of the pyramid is therefore fairly similar to the valued-added chemicals strategy presented earlier in this study.

The second most valued products derived from biomass are products such as animal feed and food items sold by the food industry. This level in this hierarchy is similar to the BSF bioconversion technology assessed in the previous chapter, which represented the Feed cluster.

Chemicals and materials such as fertilizers, bio-plastics, enzymes, or other staple chemicals are the third most economically valuable products derived from biomass (Fig. 6.1). This value category is mostly representative of the biomaterial strategy presented by Nayak et al. (2019) (Cf. Chapter 4) - although commodity chemicals may fall under the value-added chemicals umbrella.

Finally, extracting energy from biomass (energy valorization) by producing biofuel, electricity, and heat is the lowest possible strategy from an economic perspective.

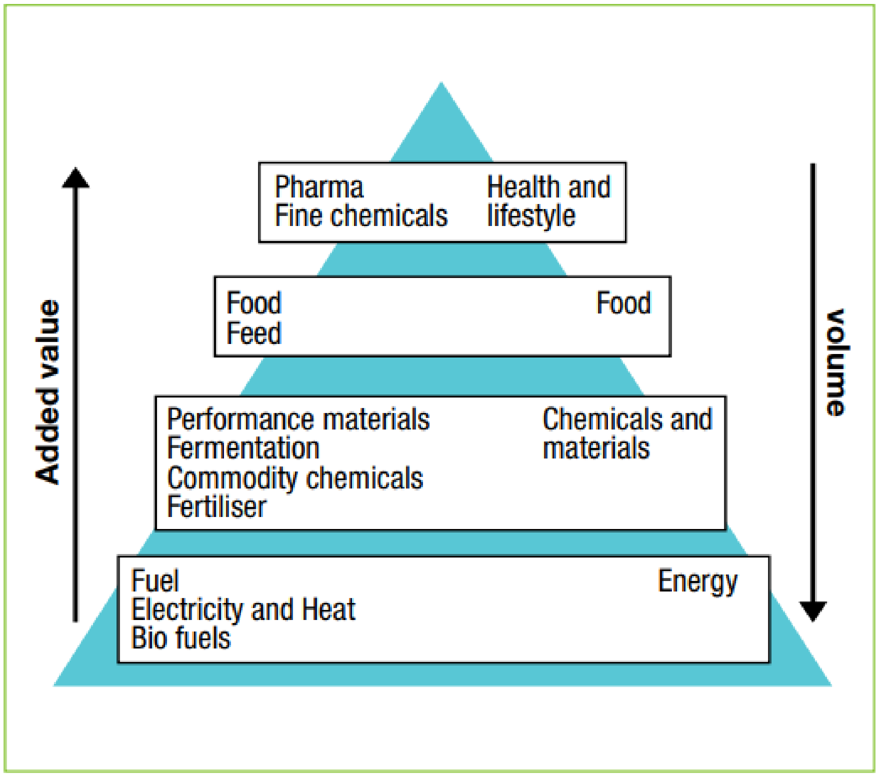


Figure 6.1: Value Pyramid from the Bio-Based Economy (Figure from Eickhout, 2012, p9)

Strengths

The main strengths of the *Value Pyramid* are visualizing the full range of options regarding FW valorization, as well as providing a simple hierarchy based on their economic value. The model shows the potential of FW valorization beyond the mainstream treatments such as digestion, composting, and incineration. Consequently, the *Value Pyramid* helps clarify and guide the FW valorization research agenda towards value-added chemicals extraction from FW and highlights the yet untapped economic opportunities regarding FW.

Limitations

The main limitation of the *Value Pyramid* is that food production is not at the top of the hierarchy. As mentioned throughout this thesis, the prioritization of biomass production towards non-food use has stirred enormous controversies in the past (e.g., energy vs. food production), and therefore should be strictly avoided.

Furthermore, by not placing food products on top of the pyramid, and only considering economic value as guidance, the *Value Pyramid* omits the moral imperative of food security (Eickhout, 2012). Therefore, to avoid defiance from the general public and the scientific community, which would negatively impact further research in biomass applications for value-added chemicals and the other strategies, food for human consumption should be at the center of a FW management framework.

Last, the *Value Pyramid* does not consider the energy and water requirements, or for that matter, any environmental consequences of these valorization strategies. The environmental performance of FW management should be part of any decision-making regarding FW management strategy, and its absence represents a substantial shortcoming for the *Value Pyramid.*

Food Waste Management Hierarchy

The FWMH framework from Papargyropoulou et al. (2014) is based on the framework developed by the European Commission on FW management strategies. The FWMH framework orders waste management actions from favorable to less favorable.

The best management option regarding FW is too avoid food surplus altogether, therefore eliminating the need of any waste collection and treatment scheme (Fig 6.2). From a FEW-nexus system perspective, this is also the best option, as it avoids the waste of the water and energy embedded in food products throughout their life-cycle (Chapter 3).

The second option relies on reusing FW production for human consumption, through re-distribution, especially towards population suffering from food insecurity (Fig 6.2). This option falls under the umbrella of the social and commercial rescue initiatives presented in Chapter 4.

Recycling food through animal feed conversion and composting is the third best option according to the FWMH. This option is in line with the biomaterial strategy presented in Chapter 4.

Energy recovery, is ranked the fourth option, and is similar to the energy valorization cluster presented in Chapter 4, although it does not seems to consider biofuels, bio-oils, and biochar.

Landfilling is the least favorable option (Fig 6.2). In Amsterdam, the option of landfilling FW is almost inexistent due to the strict waste disposal policies put in place in the Netherlands, which drastically minimize the use of landfills (Lieten et al. 2018).

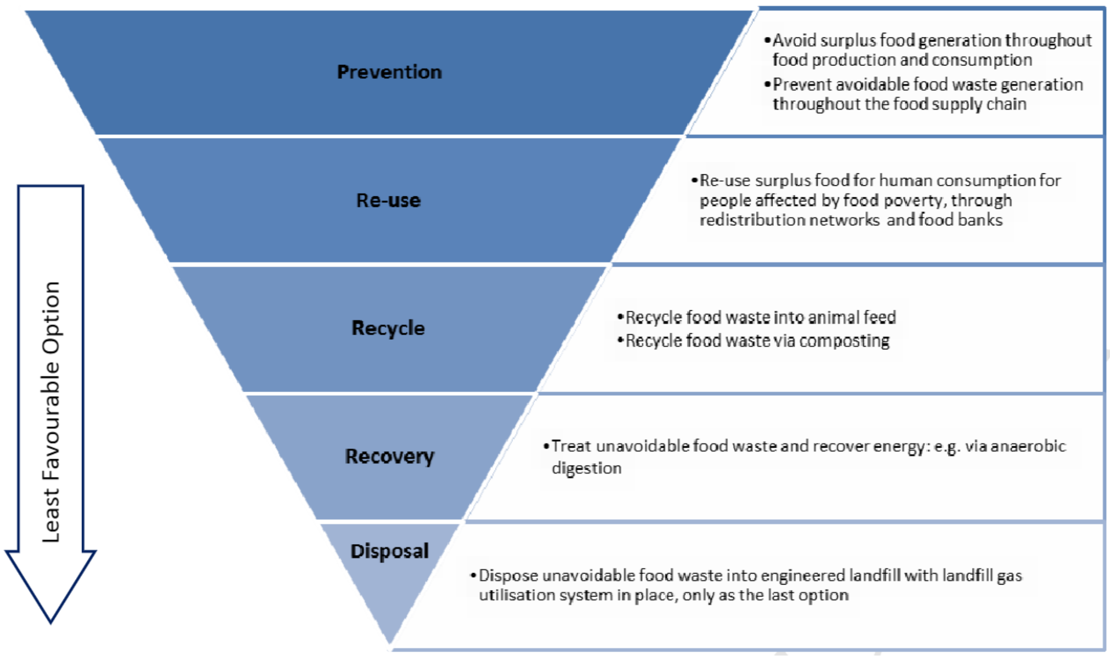


Figure 6.2: Food Waste Management Hierarchy (From Papargyropoulou et al. 2014, p107)

Strengths

The FWMH framework's strengths are that, by design, it is specifically tailored to address FW issues. More importantly, food prevention is at the top of the management options followed by food re-use (similar to FW rescue). From a FEW-perspective, these two options should be a priority due to the high amounts of energy and water waste through FW, as seen in Chapter 3. Lastly, the overarching concept of the FWMH is catered towards understanding the most beneficial management options from an environmental perspective, which makes it suited to derive the best strategy from a sustainability perspective.

Limitations

The FWH misses the important new development of biomass to create high value-added components. The absence of any bio-based concept is a strong limitation for a FW valorization framework. Furthermore, although it is based on some understanding of their environmental impacts of FW management options, it is far from being comprehensive and still represents only a general sketch of an environmental assessment (Eriksson et al. 2015). In addition, it does not explicitly address the water and energy requirements of the different options.

A New Food Waste Management and Valorization Framework

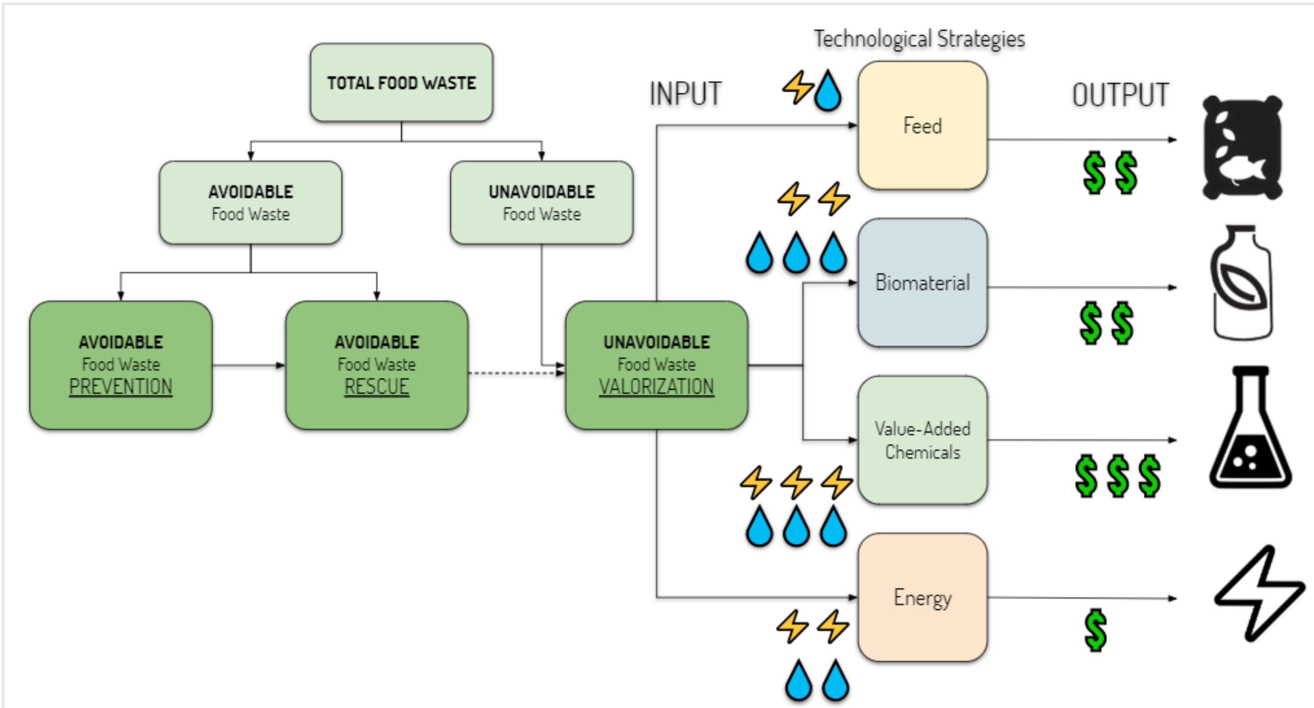


Figure 6.3: Food Waste Management and Valorization Framework

Figure 6.3 presents the conceptual FW management and valorization hierarchy framework, based on the FWMH framework, the *Value Pyramid,* and the FEW nexus system perspective developed during this study.

First, the introduction of the term "Avoidable Food Waste" and "Unavoidable Food Waste" is an importance difference with the *Value Pyramid* and the FWMH framework. As explained in Chapter 5, AFW should be the focus of FW prevention and FW rescue.

Ultimately, no AFW should be discarded in the FW management and valorization framework. Therefore, alike the FWMH, this framework puts "FW Prevention" at as the best option to manage AFW. From a FEW perspective, it will always be the favored option considering the important energy and water inputs used throughout the FSC (Cf. Chapter 3), and therefore wasted when FW is not prevented.

Preventing food surplus and FW at every step in the supply chain may also lead to significant reductions in the overall inputs of energy and water along the global food supply chain. Indeed, the global food production could be lowered to match the actual global demand- if it was not for one-third of the global food production being discarded today.

In addition, the concept of "FW rescue" is also introduced and is similar to the food re-use step present in the FWMH framework. The "FW Rescue" is considered less favorable than the first option as it is always better to prevent FW and food surplus beforehand, eliminating all together the need for establishing FW rescue initiatives. "Food Waste Rescue" entails all the social and commercial activities aiming to recover FW before the enter the waste management system.

The first two steps are therefore very different from the *Value Pyramid.* Although theoretically all AFW should be either prevented or rescued, some may occasionally still be thrown away due to unforeseeable circumstances. The dashed arrow therefore represents the potential leakages of AFW into the UFW valorization step.

The third major section of this new framework refers to the valorization of UFW. This section integrates the approach of the *Value Pyramid* towards FW valorization, in terms of the added-value of each valorization strategy, represented by the dollar icon in Figure 6.3. It shows that the value-added chemical strategy produces products with high added-value, while feed and bio-material clusters provide moderate economic outputs. The energy cluster present low economic outputs.

Additionally, the selection of the valorization options varies depending on several factors such as the status of the energy and water systems of the local environment applying this framework. Therefore, in this step, not only the economic added-value of the strategy assessed is considered, but also its performance in terms of energy and water use intensities.

The value-added chemical and biomaterial strategies are shown to use both important amounts of water to produce their outputs. Furthermore, the value-added chemical strategy is illustrated as the most energy-intensive. On the other hand, the feed appears as the technological strategy with lowest energy and water use. The energy strategy present moderate energy and water inputs.

Overall, the current framework does not provide a strict hierarchy for the valorization options. It simply presents the options with the largest and lowest economic added-value outputs and the largest and lowest energy and water inputs.

Because of the importance of the FEW nexus in this study, the energy and water intensity characteristics of these options may both receive a special weighting which would influence a final ranking order of the valorization options.

For example, in the case of both energy and water abundance for a region or a city, the valorization hierarchy should look very similar to the *Value Pyramid,* driven by economic incentives. Yet, the case of both energy and water abundance is almost non-existent across the world, whether it is from a sheer resource perspective, or considering the few countries that may fall under this scenario but have voluntary energy and water consumption reduction strategies.

Consequently, in the case of water and/or energy scarcity (or reduction strategies), the order of the valorization options would change to adapt to the local energy and water systems. As a result, each valorization strategy could be possibly hierarchized, depending on the water or energy performance, or both. In other words, thanks to a focus on energy or water savings (or both), different priorities can be set other than the sheer economic incentives of the FW valorization strategy.

In practice, a weighting system could be developed for the FEW performances relative to the economic performance, or translate the FEW performances into monetary terms, making the value-added economic performance directly comparable to the FEW nexus performances. However, it will fall under the authority of decision-makers and the local scientific community to prescribe weighting factors or monetary value for the energy and water performances.

Finally, it is important to note that the new framework purposively does not integrate any landfill option to manage FW. With the rise of the concepts such as the circular economy and bio-based economy, the waste-as-resource approach (EMF 2019; Hoff, 2011; Welink, 2015), and even of the IE field at large, it is sensible and logical to remove landfill as an option for FW treatment. As shown throughout this study, FW is a valuable resource that should not end its life-cycle in a landfill.

Application of the new framework to Amsterdam Case Study

The framework developed in this chapter is applied to the case study of Amsterdam.

Avoidable Food Waste Prevention

In 2016, about 34, 000 tons of AFW was discarded from Amsterdam's households. There is therefore an important work to be accomplished in terms of awareness, behavior change, and reduction strategies at the household-level. The issue of food surplus and FW is also an important one for the companies present in the municipality. Although, due to the lack of granularity of the companies' FW data, it was impossible to categorize their FW flows within AFW and UFW, it is highly likely that AFW is still a substantial share of their FW outputs. Change in household routines, but also change in food supply management at the wholesale and retail levels in order to avoid unsold food surplus are key to address this issue (FUSIONS, 2018; Mourad, 2016).

There are a variety of tools and strategies that may be used to spur FW prevention. Awareness campaigns such as the ones performed in Denmark to educate the public on the meaning of the Best-before/Use-by dates labels is one them (Wunderlich et al., 2018). Civil societies (e.g., Stop Wasting Food in Denmark) launching national and city-level campaigns may attract substantial support from the public and private sector and spur the development of FW prevention solutions.

Subsidy schemes to support any initiatives aiming to prevent FW can help leverage new resources (FUSIONS, 2018). Labels indicating products near expiration or "ugly" fruits and vegetables may also play an important role (Hooge et al. 2017). Thanks to Chapter 2, it was discovered that fresh bread and dairy products were the most wasted AFW. Special labels and marketing content could target specifically these products to reminds consumers of their very frequent wastage.

The introduction of “goody bags”, ubiquitous in North-America, which are bags in which restaurant and hotel customers may take away their meals left-overs are also an important solution to avoid AFW in the hospitality and food services sectors (Winnow, 2017).

The introduction of data-driven technologies, such as the ones developed by *LeanPath* or *Winnow* to track FW, control food inventory, and avoid surplus are also promising solutions to avoid FW all together in the food industry (Leanpath, 2019; Winnow, 2019). Subsidies could be offered to make some of these control systems more affordable for the restaurant and hospitality sectors to expand their use.

At the moment, Amsterdam does not have a clear and robust strategy to support FW prevention, whether at the household or private-sector level. There is therefore a need to research, plan, and implement strategies for FW prevention at the city-scale.

The solutions cited above generated through the use of the framework may all be part of this strategy. As often with prevention strategies, a mix of the different strategies highlighted is usually the most effective option.

Avoidable Food Waste Rescue

Besides households, companies located in Amsterdam produces a substantial amount of FW. Although not all of the FW is AFW, a share of it may be rescued. Amsterdam is home to many social initiatives (e.g., Instock, Taste Before You Waste) and has been an attractive market for commercial platforms such as Olio, Too Good To Go, and ResQ. Their FW rescue potential must be increased in order to capture the FW before it integrates the waste management system.

Therefore, policies targeted specifically to spur the development of these rescue initiatives must enacted. In France, it has become illegal for retail and wholesale stores to dispose their FW in the trash, and re-distribution and food donation must be arranged by the retails stores themselves (Liu et al. 2016). These types of policies may help redirect and increase the potential supply of AFW to the FW rescue initiatives.

Though Amsterdam municipality acknowledge the important roles played by these social and commercial initiatives, it does not have currently any particular policy to support them.

Unavoidable Food Waste Valorization

Amsterdam’s households produce about 31,000 tons per year of UFW. Coupled with the FW production from companies located in the municipality, UFW within Amsterdam constitutes a substantial amount of raw material, characterized by its stable supply over the medium to long-term.

As of now, the city incinerates most of its UFW through the residual municipal waste streams treated in its waste-to-energy plant (Cf. Chapter 4). The city also made available to residents a few “wormenhotels”, which are small composting system, where worms digest the FW. In addition, the municipality encourages its residents to undertake home-composting (Gemeente Amsterdam, 2019). Overall, the city of Amsterdam does not pursue actively any UFW valorization strategy, although few pilot programs are currently running (e.g., AEB’s phenol extraction pilot, Nieuw-West GFT collection pilot).

With ambitious energy reduction and renewable energy targets (25% energy consumption reduction and 25% of consumption from renewable energies by 2020), the energy performance of a UFW valorization system is particularly important for the Dutch city (Gemeente Amsterdam, 2018). As a result, the energy performance can be considered more important than the value-added and water performances of the valorization options reviewed in this study. Indeed, due its geographic location, the city of Amsterdam is far from being under threat from water scarcity, therefore the water performance, is less crucial, though not neglectable.

Amsterdam and its Main Unavoidable Food Waste Flows

The four largest UFW flows are *vegetables peels and husks*, *fruit peels*, *coffee grounds*, and *potatoes peels*, as illustrated in Chapter 2. These four flows represent 90% of all UFW flows from Amsterdam’s households. Therefore from a sheer volume perspective (in tons), these four UFW flows will be the largest feedstock available. Thus, they should be the focus of valorization strategy at the city-level. Additionally, these FW streams may also be produced in large quantities by companies throughout Amsterdam, especially in the *Food Services and Restaurants* (NACE 56.0), *Hospitality* (NACE 57.0), and *Retail Stores* (NACE 47.0) sectors.

Furthermore, this supply of UFW will be stable over the medium to long-term to justify the investments needed for the FW valorization infrastructure, from a business perspective (Mirabella et al, 2013; Maina et al. 2017). On the other hand, it is important to underline again that the current large AFW flows cannot be used as a justification for such investments, as the primary goal remains their prevention or rescue through the social and commercial initiatives.

Vegetable peels and husks, potatoes, *fruit peels,* and *coffee grounds* present a strong advantage, as they are readily useable in a variety of applications (e.g., anaerobic digestion, composting, and BSF bioconversion) (Nayak et al. 2019; Mondello et al. 2016).

Furthermore, if the city of Amsterdam wishes to pursue its exploration of cutting-edge FW valorization technologies, these four FW streams are adequate as bio-feedstock for a multitude of bio-processes. Indeed, v*egetable peels and husks, potatoes peels*, *fruit peels*, and *coffee grounds* are also well-researched for bioethanol production (e.g., coffee, mandarin, banana), and to a lesser extent for value-added chemicals extraction, especially regarding *fruit peels* (e.g., citrus, apple), and even bio-adsorbent (e.g., coffee, banana, orange) (Kefale et al., 2012; Oberoi et al. 2011; Sandhu et al. 2012; Lam et al. 2018, Pfaltzgra et al. 2013;

Boonamnuayvitaya et a., 2014). Nonetheless, more researched is needed for the value-added chemicals strategy regarding their energy and water intensity, as mentioned previously throughout this study.

Selecting the Most Promising UFW Valorization Options for Amsterdam

Among the 12 technologies considered throughout the previous chapter, a few of them present practical and technological barriers. Thus, a selection must occur to select the technologies with the most promising outlook considering Amsterdam's UFW context.

Value-Add Chemicals

Firstly, the value-added chemical strategy regarding FW valorization is still an emerging field. Consequently, the extraction processes of HMF and pectin from FW feedstocks is mostly taking place at lab-scale (Nayak et al., 2019).

Secondly, it was shown in the previous chapter that these extraction processes require very high amounts of energy compared to other valorization processes. With ambitious energy reduction targets, Amsterdam's strategic orientation may therefore conflict with this option.

Thirdly, there are still a lot of uncertainties regarding the large-scale feasibility, although recent findings suggest that pectin and essential oils extraction from FW may be cost-efficient (Pfaltzgraff et al., 2013).

Lastly, HMF, pectin, and other chemicals extractable from FW usually requires a pure and homogenous waste stream (Pfaltzgraff et al., 2013). Therefore, considering that Amsterdam's main FW providers are the households, the chemical strategy may not be the best suited currently to treat Amsterdam's FW. Yet, it is important to remain attentive in the near future to new developments in this field, as new opportunities to extract value out of FW are frequently created (e.g., Peel Pioneers).

Bio-materials

Considering the bio-material strategy, bioplastics have both high energy and water requirements, therefore making it not favorable from a FEW nexus perspective. In addition, it may be produced through specific waste streams (e.g., cane sugar, starches) and therefore the FW produced by Amsterdam's households may not constitute the most adequate feedstock.

Second, the high energy requirements are also a key characteristic of enzyme production. Enzyme production seems to provide interesting economic returns, though uncertainties remains regarding its water use, and it is not clear if the Amsterdam metropolitan area has the demand for such a product or even the pool of expertise required to join this industry. In addition, a pure stream of FW (e.g., potatoes) would be required, which may be again be difficult to achieve in practice, considering households' FW heterogeneity.

Last, the production of bio-adsorbent from wastewater treatment plant is still in its infancy (Nayak et al. 2019). Thus, it would not be a solution readily applicable in Amsterdam. Furthermore, it is not clear if the main water treatment company (i.e., Waternet) would be interested in such a material for its own infrastructure.

Energy, Feed and Composting

Anaerobic digestion, composting, pyrolysis, incineration, biofuels, and BSF bioconversion are technologies that have been proven profitable and implementable a at large-scale (Nayak et al., 2019, Mondello et al. 2018, Protix, 2019).

Furthermore, Amsterdam's municipality and its waste management stakeholders have been active and investing in most of these technologies within the energy valorization and bio-material strategies (Cf. Chapter 4). The city has therefore the current capabilities and pool of expertise (e.g., AEB, Orgaworld, Meerlanden; GoodFuels) to establish any of these technologies. Regarding BSF bioconversion, the Dutch company *Protix* illustrates the maturity, economic viability and the presence of expertise on this technology near Amsterdam.

Although at first glance, waste-to-energy incineration and pyrolysis may produce a substantial amount of energy (Fig A3, Appendices), they are very inefficient in terms of energy use due to the high moisture content of FW (Nayak et al. 2019), and therefore are not adequate to valorize Amsterdam's FW.

Biofuels is by far the most energy-intensive FW treatment process from the energy cluster. Moreover, considering again the heterogeneity of the FW, biofuels production may be more suited for industrial food plants producing large amounts of fatty and oily wastes (GoodFuels, 2019). These waste streams are not present in sizeable amounts within Amsterdam's boundaries.

Further, considering the energy and water requirements of these most promising options, the results of Chapter 5 show that composting, anaerobic digestion, and BSF bioconversion are the least energy and water intensive solutions for the treatment of FW in Amsterdam.

Furthermore, a strong advantage of these three options is their capacity to treat somewhat heterogenous FW flows (Mondello et al. 2018; Nayak et al. 2019). *Vegetables peels and husks*, *fruit peels*, *coffee grounds*, and *potatoes peels* are feedstocks readily useable for these three technologies that can treat these four waste flows at the same time. Last, anaerobic digestion and BSF bioconversion do provide some revenues from the sales of their outputs (Cf. Chapter 5). Composting would also provide minimal revenues.

Consequently, from the FEW assessment performed in Chapter 5 and the guidance of the new framework to choose an UFW valorization strategy, anaerobic digestion, BSF bioconversion, and composting appears as promising technological strategies for Amsterdam.

Table 6.1 presents the potential outputs stemming from the treatment by these three suggested technologies of the total amounts of the *vegetable, fruits, potatoes, and coffee grounds* UFW flows from Amsterdam's households.

Table 6.1: Outputs Comparison of the Suggested Technologies for Amsterdam				
Technology / Outputs	**AD**	**BSF Bioconversion**	**Composting**	**Units**
Biogas	5741994	0	0	m3/yr
Digestate	17451	0	0	ton /yr
Compost	0	9429	14073	ton /yr
BSF Feed	0	844	0	ton /yr
Energy	0.135	0	0	PJ/yr

As the only technology selected from the energy cluster, anaerobic digestion is the most promising from an energy perspective. It has low energy inputs and produces biogas contributing to the renewable energy targets of the city. It also produces digestate residues, rich in nitrogen, phosphorus, and potassium, that can be used as a biological fertilizers (Tambone et al., 2010). It scores relatively low in the value-added category (cf. *Value Pyramid;* Chapter 5) but this tradeoff is moderate due the importance of renewable energy production for Amsterdam.

The treatment of the targeted UFW flows will generate 0.12 PJ of heat per year assuming a methane content of 63% for the biogas produced, and a combined heat and power (CHP) efficiency of 90%, consistent with the literature (SGC, 2012; Zhang et al. 2007; Hakawati et al., 2017). The useful energy produced from the anaerobic digestion treatment of the UFW therefore amounts to 0.62% of the energy consumed in the residential sector of Amsterdam (with 2012 as a base-year). More practically, it could power about 3 200 households in Amsterdam. While it may not seem substantial, it will contribute to Amsterdam's renewable energy targets (i.e., 25% of energy consumed from renewables).

Additionally, the production of biogas might be increased by augmenting the supply of feedstock through the acquisition of the FW produced by businesses located in the city (Cf. Chapter 2) or by sourcing agricultural and horticultural residues from the surrounding region.

It is worthy to note that the energy required (direct energy input, cf. Chapter 5) to treat the selected UFW flows through an anaerobic digestion plant, represent about 6% of the total energy production from the digestion of these UFW flows (7 GJ consumed and 122 GJ produced). Furthermore, comparing the net energy produced by the anaerobic digestion, to the cumulative embedded energy over the life-cycle of the UFW flows of *vegetables, fruits, coffee grounds, and potatoes,* the anaerobic digestion process recovers a net energy of 114 GJ while the cumulated embedded energy of these four UFW flows are quantified to be 615 GJ (assuming an energy allocation by mass between the AFW and UFW flows of these food products). Thus, anaerobic digestion energy production may potentially help offset the overall embedded energy of these UFW by about 19%, although the embedded energy of the anaerobic digestion plant over its life-cycle is not considered here.

The anaerobic digestion of the households' UFW will also generate a large amount of digestate that could be use as fertilizer in parks, private garden, and on agricultural lands around the city. Although the Netherlands have been experiencing in recent years excess production of manure from its livestock industry, the production of high-quality fertilizer and soil improvements, derived from non-animal organic waste or combined with manure, has been encouraged, especially for export purposes (Wageningen UR Livestock Research, 2014).

Bioconversion using BSF digestion utilizes low energy and water inputs and produces two useful products: high-grade compost and insect feed that can be use in aquaculture; where feed is often considered as the main contributor of environmental impacts (Aubier et al. 2013; Pelletier et al. 2009). The BSF bioconversion could generate potentially about 844 tons per year of BSF larvae that can be use as fish feed. It would also generate about 9, 423 tons of high-grade compost that can be use in public parks, for private garden, or in the surrounding hinterland. According to the pricing from the Dutch company Protix, that produces BSF-based insect feed, this yearly production could potentially generate about 2.5 million euros of revenues for unprocessed BSF larvae, and between 4.2 and 8.4 million euros of revenues for processed BSF protein powder (AllAboutFeed, 2016).

Composting has the lowest water and energy inputs and produces only compost. An industrial composting plant could produce up to 14, 073 tons of compost simply by using the UFW from vegetable, potatoes, fruits, and coffee from Amsterdam's households. Again, this compost may be use in variety of locations (e.g., parks, gardens, horticulture).

Conclusion

Overall, this chapter presented a new framework that goes beyond the *Value Pyramid* and the FWMH framework, using them both along with the FEW insights developed in this study to make a comprehensive and coherent framework that gives a clear direction for the city of Amsterdam.

FW prevention strategies must be developed and enacted at the city-level. Educational campaigns to educate about the best/Use before date labels should be launched on the model presented by cities in Denmark. Social initiatives can help bring this educational knowledge at the grass-root level. A focus on communicating on bread and dairy wastes could help target these two (largest)AFW flows. The promotion of "goody-bags" to take-away unfinished meals in restaurant must be encouraged and become a habit for both restaurant and food services and their customers.

Awareness campaign to educate Amsterdam's residents about the energy and water embedded in the food products they consume may also encourage them to prevent FW. The creation of labels to promote the sales of ugly fruits should be use at the retail-level, and city-wide. The city could offer subsidies to promote the purchase and use of FW tracking and management software in wholesale, restaurants, and food services. Therefore, educational campaigns, labels, and subsidies may be used in combination to prevent FW at the city-level.

The social and commercial initiatives must be supported by further influencing the wholesale, retail, food services, and hospitality sectors to redirect their AFW toward useful initiatives. This can be done through waste disposal policies on the French model, enacted across the city, where whole sales and retail stores are required to seek organization to donate their soon-to-be FW, rather than discard it in their trash (Liu et al. 2016).

Concerning the UFW, a focus on four UFW flows, *vegetable husks and peels, fruit peels, coffee grounds,* and *potatoes peels* should be favored. These UFW flows are readily useable in many valorization application. Moreover, a limited numbers of waste to target may help to separate these useful waste more efficiently. Considering the energy ambitions of the city, anaerobic digestion may be a strong solution, although BSF bioconversion, and composting are also interesting options to consider for the useful outputs (especially BSF bioconversion) and their good FEW performances. The option to recover value-added chemicals extracted from Amsterdam's UFW requires much more research to be pursued on the subject.

Last, this framework facilitated the generations of two distinct over-arching strategies by introducing explicitly the notion of UFW and AFW. The first one is aiming to minimize AFW through prevention and rescue and the other maximize the value of UFW, all while considering Amsterdam's context and the FEW nexus perspective.

Chapter 7 – Amsterdam Food Waste Strategy: Stakeholders Importance and Roles

Introduction

The municipality of Amsterdam is in charge of the waste collection of households and has the authority to decide how businesses ought to take care of their waste. Additionally, the city of Amsterdam is interested in implementing a new strategy to recover and valorize its organic waste streams. It will have therefore a central role in the development of a future FW scheme. To do so, the city must identify its most important stakeholders.

This chapter therefore offers an overview of the power and interests of the different stakeholders related to Amsterdam's FW flows and the establishment of a FW management and valorization scheme. Then, the roles of each stakeholder are suggested in a future FW scheme in an attempt to clarify such a project.

Implementing a FW valorization strategy with Amsterdam FW Stakeholders

Interests and Power of FW Stakeholders

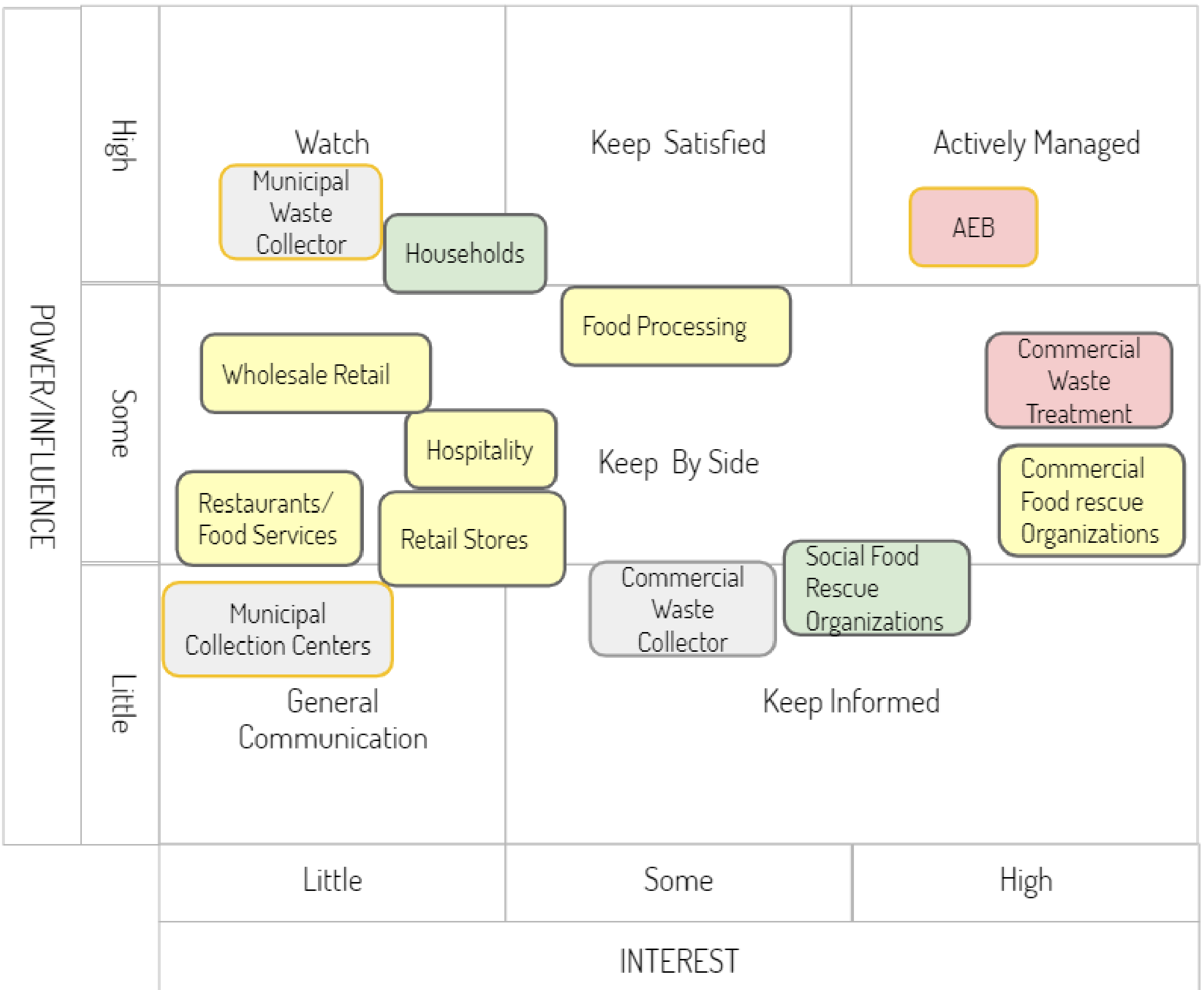
In order to implement the valorization strategy outline in the previous chapter, stakeholders related to the FW flows of Amsterdam must be considered and their importance assessed.

The following stakeholders play a role in the current and future FW flows: the municipality of Amsterdam, AEB, the WtE plant, the households, the municipality waste collectors , Renewi, Suez and other commercial waste collectors, Orgaworld and other commercial biowaste treatment plants, the social (e.g., Taste Before You Waste) and commercial initiatives (e.g., Too Good to Go) rescuing FW, the different food sectors of Amsterdam, and the different research groups and consultancies that have informed the municipality of the value of its organic waste streams.

The power/interest matrix developed by Newcomb (2003) was used in order to identify the role and importance of the different stakeholders for the implementation of a FW valorization strategy for Amsterdam. This step aims to further the analysis started in Chapter 1, while answering Daher et al.'s question: *how do we communicate? When do we involve stakeholders in the process?*

Such matrices are often used as analytical and planning tools during multi-stakeholder processes (Hunjan & Pettit, 2011). The matrix aims to comprehend the degree to which Amsterdam's FW stakeholders, identified in Chapter 1 have an influence over the creation of a FW management and valorization program in the city. It also assesses their level of interests vis-à-vis such a program.

The power of stakeholders illustrates their importance and indicate which stakeholders must have their needs satisfied in order for the valorization scheme to be implemented successfully, without blockage. A stakeholder with high power may have the capacity to halt or facilitate a FW valorization scheme (Hunjan & Pettit, 2011). The interest axis enables to understand, which stakeholders will be easily on board with such a project and act as allies, and whom that will need more convincing (if their influence is important, and therefore needed) (Hunjan & Pettit, 2011).



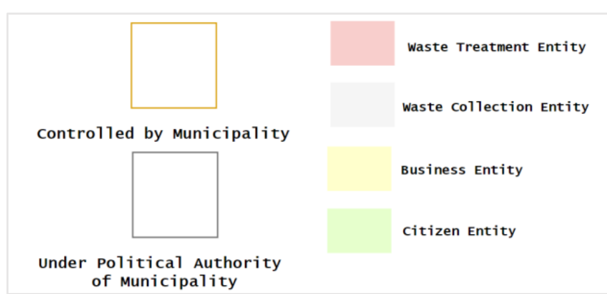


Figure 7.1: Power/Influence-Interest Matrix for Amsterdam's Food Waste Stakeholders

Figure 7.1 gives a rapid overview of the positions of Amsterdam's FW stakeholders relative to the realization of a FW management and valorization framework.

First, the most interesting feature is related to the position of AEB, the WtE plant of Amsterdam. Over the last two decades, AEB has shown leadership and an innovative character in the field of sustainable WtE. Furthermore, it has shown great interests in exploring new ways to extract valuable resources from its waste flows, as illustrated by its numerous pilot projects (e.g., phenol recovery, CO2 capture) and research partnerships (e.g., TNO, TUDelft, Wageningen University). As it is currently the largest receiver of Amsterdam's FW flows, it is one of the stakeholders with the highest leverage on the operationalization of a future FW scheme.

Second, the municipal waste collectors appear a stakeholder with low interest and high power of the creation of a FW scheme by Amsterdam Municipality. The municipal waste collectors have no interest in taking the charge of new collection scheme, at least without a substantial amount of new resources and financial incentives. In 2010, the municipal waste collectors organized a week-long strike to protest their wage level, which paralyzed the entire waste collection system of the city. Although the implementation of a new FW scheme may not lead to such an extreme situation, it is of primal importance to bring on board the waste collectors for a successful FW scheme. Their role will also depend on the type of collection procedures chosen for FW, whether it is a new separated stream or households and companies must go to collection points to dispose of their FW.

Commercial waste collectors such as Renewi may have substantial interests in a FW collection scheme for businesses as they could provide an additional service and expand their business activities. Certain companies could even be interested in providing processing activities. Overall, most FW flows originate from households within Amsterdam Municipality boundaries, therefore they have a lesser influence compared to municipal waste collectors.

Commercial food rescue platforms such as Too Good To Go may have some interests in finding arrangements or lobbying the municipality to make their platforms more visible, and an alternative for businesses to choose from, in terms of FW management options. On the other hand, a reduction in the amounts of AFW through FW campaigns and policies may compete against their business models. The power of commercial online platform resides in their large-scale FW recovery offering and their public reputation in addressing effectively the issue of FW, but it is overall limited vis-à-vis the municipality.

Social food rescues initiatives have a relatively high interests in a FW scheme, but they do not have enough resources (e.g., man power, money, connections) to have a sizeable impact on policies. Their main influence is derived from the ability to raise awareness through public campaigns that may result in increasing the public pressure on the city's authorities, swaying legislations and the city's commitments to address FW issues (e.g., Stop Food Waste in Denmark). Social initiatives may be rather interested in the FW collection aspects of a FW management and valorization scheme, at the condition of not losing their autonomy and their social purpose, two fundamental features of these projects.

It is difficult to assess the overall power and interests of businesses in the different food sectors due to the high variety of businesses. Some companies interested in lowering their waste collection fee and/or receive tax rebate may have significant interests in a valorization scheme. Furthermore, some progressive companies may just wish to act pro-actively and partake in the latest developments in the circularity and sustainability fields and perhaps even create new revenue streams from their FW. For other, the costs and apparent logistical burdens of a new valorization system might be considered a hindrance, and consequently reduce their overall interest. The power of businesses is somewhat sizeable, especially with large business associations (e.g. Dutch Dairy Association), which may be in the capacity to lobby the municipality toward a favorable outcome for them through a valorization scheme.

Households in Amsterdam do not have a strong interest in separating their waste. There are few neighborhood-scale projects attempting to create their own organic waste collection, for example at Java-Eiland, but by and large there is no evidence that suggests a strong desire to recover FW (e.g., no large public petitioning, limited number of neighborhood projects such as the one on Java-Eiland). However, households have a strong power over the future success of a FW management and valorization scheme due to the sheer volume of FW they produce (cf. Chapter 1). Moreover, households are ultimately decisive in orienting the current administration in charge thanks to their voting power.

Conclusion

Overall, AEB is an ideal partner for the city of Amsterdam, it has both high interests and a high influence in a FW scheme. Households, followed closely by the municipal waste collectors, constitute the most important stakeholders to bring on board through communication campaigns, public hearings, and negotiations (for the collectors). Their high-power but low interests must thus be overcome. The position of the businesses producing FW across the industry must be clarified. It will be advantageous to identify which of them converge tightly towards the objective of a FW management and valorization scheme.

A few companies also produce large amounts of FW (Cf. Chapter 2), which represent interesting sources of homogenous FW. These few companies may help to acquire rapidly large quantities of FW for the valorization, enabling larger flows, and realizing economies of scales. Commercial waste collectors, specialized in resource-recovery (e.g., Renewi, Suez) appear to be important actors to outsource the collection of FW to.

Potential Roles of FW Stakeholders

In a future FW scheme at the city-scale, the roles of each Amsterdam FW stakeholder must be clarified. Using the stakeholder role matrix developed by Tennyson (2011), the roles of Amsterdam stakeholders for a future FW valorization scheme are suggested in Table 7.1. These roles may not be fixed and evolve over time due to unforeseen circumstances, tensions, and new stakeholders joining the project (Tennyson, 2011).

Table 7.1: Stakeholder-Role Matrix of Amsterdam's future FW valorization scheme	
Role	**Stakeholder**
Partner *A core decision-maker, very active in the implementation of the project.*	AEB; Amsterdam Municipality
Contractor *Accomplishes key tasks in the project.*	Municipal and Commercial Waste Collectors
Influencer/Champion *Uses reputation to establish an authoritative profile to the project.*	AEB
Disseminator *Act as advocate and advertise the benefits and merits of the project.*	Amsterdam Municipality; Social Rescue Initiatives
Funder *Contributes financially to the project.*	Amsterdam Municipality; AEB; Commercial Treatment Plants
Informer/Consultation *Provides bottom-up information and feedback on the project's outcomes.*	Amsterdam Food-related Businesses; Households; Commercial Rescue Platforms
Knowledge Provider *Provides key information to facilitate decision-making.*	Consultants (e.g., CREM; Metabolic, Kantar Public); Academics (e.g., REPAIR team);
Regulator *Ensures the legality and the enforcement of the project activities*	Amsterdam Municipality
Beneficiary *Benefits from the project outcomes.*	Amsterdam Municipality; Commercial and Social Rescue Initiatives; proactive food businesses
Other	Amsterdam Collection Centers;

Because of its size and reputation, AEB would act as a partner and a champion in such a scheme (Tennyson, 2011). It may play a key role in the design and the implementation of a FW valorization plan. It also has the capacity to promote a new stakeholders' partnership for a FW scheme, thanks to its professional reputation, giving the FW scheme further authority alongside the municipality.

The municipal waste collectors and the commercial waste collectors may act as contractors, executing the tasks of collection of FW at the households and businesses. This role will be key to filling up the needs of a stable and relatively homogenous supply of UFW (i.e. the four flows identified in the Chapter 6) in the valorization plant.

The municipality will have several roles. First, it will be a core partner of the project as it will be one of the main decision-makers in the design and implementation of a future FW scheme due to its central position and authority over FW management across the city.

Second, it may act as a funder with the investment required, although AEB and commercial plants such as Orgaworld may also bring a share of the investments needed for an anaerobic, BSF bioconversion, or composting plant construction, as well as for the collection infrastructure required to be created or expanded.

Third, the municipality will also have to act as a regulator. Whether it is to enact policies in order to increase the flows of AFW from wholesale or retail stores towards social and commercial rescue initiatives (Cf. Chapter 6) or to implement a FW collection system for Amsterdam households, Amsterdam municipality will be in charge to make these policies enforced successfully.

Fourth, the municipality central position would make it a central disseminator of the project's goals and purposes. However, social rescue initiatives may also play a key role at the grassroot-level, thanks to their social platforms within Amsterdam's neighborhoods. They may inform and educate through their workshops and social events the residents of Amsterdam in understanding better the difference between AFW and UFW, and which key UFW they should isolate (e.g., *vegetables husks and peels, fruits peels, potatoes peels, coffee grounds*). They may also educate on the Best/Use-by labels that are frequently poorly understood by consumers (Boxstael et al. 2014; Milne, 2013).

Households, FW-producing businesses, and commercial rescue platforms may all be consulted or used as informers.

Households may be consulted to better understand their needs within the application of FW scheme and find the most favored and efficient way to collect their UFW. This is especially important due to their high power of households over the implementation of a FW scheme, as explained previously. Feedback may be collected by its residents in order to improve the understanding of the outcomes of the FW scheme on the public.

FW-producing businesses may be consulted to identify further the barriers and opportunities seen by these businesses vis-à-vis their FW management. Pro-active and committed businesses may even take a leading role in advocating for the recovery of UFW and prevention and rescue of AFW.

Last, commercial rescue platforms may be able to provide some information on the different trends across retails stores and restaurants in terms of making their AFW available for free or for discounted prices. With the strictest privacy protections implemented, nonidentifiable relevant data might be shared such as where AFW is mostly collected in Amsterdam, at which rate, and if certain seasonality or temporal trends are present throughout the year.

Consultancies and academic experts would act as knowledge providers to facilitate the creation of a FW scheme. Experts like the teams from CREM, Kantar Public, or the REPAIR team can bring valuable knowledge and provide expertise on the best way to collect and use the identified UFW streams. Due to their experience (e.g. CREM surveying practices), they may support the municipality of Amsterdam in the consultation of households and businesses. The Amsterdam Economic Board may also be an interesting knowledge party to bring on board. They may share their knowledge on the circular economy and waste management, and the recent business models around biorefineries they have been overseeing (Amsterdam Economic Board, 2018).

There are several beneficiaries from the FW scheme.

First, the municipality of Amsterdam will join the rank of other Dutch municipalities that already collect organic waste. Amsterdam ambitious sustainability-related goals are aligned with such a FW scheme. Thus, a successful FW scheme will reinforce the reputation of Amsterdam as a pro-active metropolis when it comes to sustainability and circularity commitments.

Second, social initiatives and commercial initiatives may benefit from a successful implementation of AFW, where more pipelines of donations/discounted baskets are provided due to policies aiming to avoid retails stores and wholesalers to discard their AFW in the trash.

Third, pro-active businesses may also reap some benefits from using their FW for valorization processes, reducing their waste collection costs, creating value from their waste streams, and contributing to their progressive/forward-looking reputation.

Finally, households may benefit by reducing the volume of their residual waste streams, and by the sense of belonging in a pro-active city in terms of waste issues.

Waste Collection Centers are classified in the stakeholder's category "Other" as it is unclear what role they could play in a potential FW scheme. Nonetheless, their role of waste collection hubs may be valuable for a future FW scheme.

Conclusion

By and large, it will be the role of the municipality of Amsterdam to regulate and invest (at least partly) in the establishment of a future FW management and valorization scheme. In such a project, AEB's role would be central and it would likely act as a core partner to the municipality of Amsterdam.

Households and FW-producing businesses must be consulted frequently throughout the decision-making process and while the scheme is operating, both to provide and receive information useful to the success of the FW scheme.

The large pool of social FW rescue initiatives is an asset for Amsterdam, as it can provide a grass-root support for such a project, performing educative work in Amsterdam's neighborhoods.

The municipality must also thrive to use the existing expertise on FW that has been established by leading academic projects (e.g., REPAIR) and consultancies' reports (e.g., CREM).

The commercial waster collectors and treatment plants may all offer some support by being contracted or providing joint-investment opportunities to help create a city-wide UFW valorization programs.

FW-producing businesses will need to either voluntarily or abide by (if established) the policies making them responsible for connecting their AFW to social rescue initiatives.

The municipal waste collectors will need to provide a new collection service to acquire the UFW from households, or they may be supported by other commercial waste collection contractors.

Overall, this chapter helped further characterized the important FW stakeholders of Amsterdam, by understanding their influence, their interest, and their potential roles in a future FW scheme. This resulted in refining the outline of a potential FW strategy for the municipality of Amsterdam.

Chapter 8: General Discussion and Final Recommendations

This study provided new information and important insights through its FW MFA results, the analysis of the embedded energy and water in Amsterdam's food flows, the inventory of the social and commercial FW rescue initiatives, the FEW assessment of 12 FW valorization technologies, the development of a new FW management and valorization framework, and the characterization of Amsterdam's FW stakeholders.

This chapter discusses further these results, reviews the advantages and limits of the FEW nexus perspective, make some recommendations for the municipality of Amsterdam and for research practitioners in the fields of FW and the FEW nexus, and presents future research pathways.

The Advantages of the FEW nexus Perspective

The FEW nexus system perspective in this study enabled to uncover numerous insights on the interactions of energy, water, and food for this FW study.

First, the FEW nexus perspective established in Chapter 1 enabled the understanding of the interactions of the energy, water, and food throughout the entire FSC, fostering the adoption of a system-perspective to study FW. This is key as it made clear that the food, energy, and water impacts extent far beyond the boundaries of Amsterdam. This realization is consistent with Heard et al. (2017) that, together with other studies, emphasizes that despite their restricted size, cities have an overwhelming impacts at a global-scale. Their impacts are due to the enormous amounts of resources funneled towards them to provide a livelihood for urban dwellers.

Second, though not new *per se*, this study highlighted food products (e.g., meat) that are resource intensive at a city and household-level. Their subsequent spoilage contributes to a large share to the overall energy and water wasted through FW. This also illustrates the threat of an additional burden driven by dietary changes that would add new pressures on the energy and water systems by consuming more meat, more refined sugars and fats, and generally more food (Heard et al. 2017).

The impacts of dietary choices on the environment has been increasingly put forward in academia (Springmann et al. 2018; Macdiarmid et al., 2016). For example, an increase in meat consumption will have a rippled negative effects on the local and global water and energy systems, as well as have implications for the phosphorus and nitrogen cycle at the regional level (Springmann et al. 2018; Hou et al., 2010). This study's insights, on the energy and water intensity of Amsterdam's households' food consumption, are also useful in the European context, where diets are relatively similar despite regional variations (Birt et al. 2017).

European countries have broadly speaking similar dietary guidelines to inform the general public about healthy food (Montagnese et al. 2015) yet the emergence of sustainable dietary guidelines is still in their infancy (Springmann et al., 2018). As Springmann et al. (2018) explored in their milestone study on a sustainable food system, healthy diets and sustainable dietary guidelines must be increasingly aligned.

However, providing solely information will likely not be able to change individuals' diets. It may even be met with resistance due to a lack of awareness between the relationship of dietary choices and environmental impacts (Macdiarmid et al., 2016). This study contributes to the informational component about the energy and water costs of the food consumption in Amsterdam, yet this information must be coupled with economic incentives, educational efforts, and other visible changes to create effective behavior change (Springmann et al. 2018). This study's findings however, provide relevant data for a future study on behavior change, dietary guidelines, and environmental impacts related to food consumption in Amsterdam, and Europe.

Third, the FEW-nexus system perspective made insightful that some technologies, despite being commonly thought of as innovative solutions, are extremely energy and water intensive. Value-added chemicals extraction from FW, and to a lesser extent, of bioplastics, enzyme and biofuel production have very high energy intensity. This is consistent with the warning by Bello et al. (2019) on the often-unnoticed important energy requirements for emerging biorefineries processes. The insight of the threat of a burden-shift onto other systems (i.e., water, energy) is a key perspective brought through the FEW nexus system perspective.

These results stemming from the FEW perspective was key to suggest anaerobic digestion, BSF bioconversion, and composting for Amsterdam's FW. Indeed, understanding the energy and water intensity of these valorization technologies through their FEW assessment made possible to suggest technologies coherent with the energy and circular policies being implemented or envisioned by the city (Hoek et al., 2015).

Additionally, more research is needed on the energy and water intensity of these new technologies. Bello et al. (2019)'s study is an encouraging step in the right direction as it aimed to provide the energy footprint of a biorefinery. Their work is the first of this kind, and although it focuses on a lignocellulosic feedstock (e.g., wood), it clearly maps the variety and complexity of the biorefinery's processes and their energy inputs (Bello et al. 2019). A similar effort should be made for biorefineries focused on FW-based feedstocks. Currently, there is no such overview available for the water footprint or water intensity of biorefinery processes (Kibler et al. 2018). This knowledge gap is confirmed in this thesis.

The Limitations of the FEW nexus Perspective

The FEW nexus system perspective is not a bullet-proof analytical framework and leaves some questions unanswered. Three limitations may be highlighted: the strong focus on water and energy impacts may lead to not considering other relevant environmental impacts; the lack of governance analysis in the FEW nexus approach, and the lack of communication strategies.

First, the FEW nexus approach leaves out important aspects regarding the assessment of valorization technologies, such as emissions, whether from an air pollution perspective or a nutrient perspective. For example, Mondello et al. (2018) considered a total of 12 impact assessment indicators, such a Global Warming (in carbon dioxide equivalent), Land Use, Eutrophication, or Marine Aquatic Ecotoxicity.

By and large, LCA studies can help assess the different treatment technologies (Opatokun et al., 2017; Laso et al., 2018; Mondelo et al. 2018) and complement the results provided by a FEW nexus analysis (Mannan et al., 2018). For example, Mondello et al.'s results show composting to have a larger global warming impacts, freshwater ecotoxicity, and larger impacts in most of the environmental impacts assessed compared to biogas production through anaerobic digestion and BSF bioconversion. Therefore, a further analysis of the emissions of the three technologies suggested in this study to treat Amsterdam's FW may results in slightly modifying the final recommendations made to the city.

An issue remains that LCA results are very sensitive to their system's boundaries and there is discrepancy between a methodology that would inform the energy and water use in the local context related to these impacts and along the entire supply chain. Last, carbon footprint related to household food consumption can also present relevant additional information on the impacts of food consumption (Saner et al. 2016).

This study's results therefore only offer one part of the picture, though one that is often neglected, and could be substantiated with pollutant emissions and other environmental impacts caused by the technologies and strategies reviewed in this study.

Furthermore, the FEW nexus concept does not bring a clear understanding of the governance processes taking between and within these three systems. This a key critic of the approach and was comprehensively reported by Hoolohan et al. (2017). This study aimed to partly remedy this issue by analyzing the different stakeholders relevant to the FW flows of Amsterdam.

This step was first done by answering Daher et al. (2017)'s seven questions, bringing early on the question of stakeholders at the center of this study. Yet, answering these questions were not enough to fully understand the few important actors crucial for the establishment of a FW management and valorization strategy in Amsterdam. Therefore the use of the *influence-interest*, and *stakeholder-role* matrices were useful in pushing a step further the stakeholder analysis. As a result, this study helps identify the key FW stakeholders in Amsterdam, understand their importance and interests, as well as define their potential role in a future FW management and valorization system.

Nonetheless, further work would be needed to further the analysis of the different institutions and organization overseeing the local water, energy and, food systems of Amsterdam. Classifying the actors within their respective nexus sectors may a first step towards to map out their actions and the implicit and explicit linkages between the systems' governances (White et al. 2017). Additionally, the benefits from an increase in cross-nexus sectors discussion should not be taken for granted (Wichelns, 2017).

Last, it is important to take in further consideration the importance of communication for the establishment of a FW management and valorization scheme. The important amount of new information of Amsterdam's flows and their FEW-nexus impacts presented in this thesis will not be enough to spur the development of a FW scheme at the city-scale (Helmsted et al., 2015).

Turning this information into useful decision-making knowledge is required. Helmstetd et al. (2015) provide very useful insights in the field of FEW nexus communications. For example, the co-production of knowledge with researchers, Amsterdam's policy-makers, and regional practitioners may be an effective way to engage decision-makers; By incorporating decision-makers in the research process, the results would become more transparent and tangible for the relevant authorities (Helmsted et al., 2015).

A New Framework for FEW nexus and FW studies

This study provides a new FW management and valorization framework to guide FW strategies. By combining the FEW nexus perspective, the FWMH framework and the *Value Pyramid*, it offers a comprehensive and coherent framework. It is comprehensive because it regards both AFW prevention and rescue, and UFW valorization. It thus brings forward the valorization opportunities brought about by the bio-based economy, without neglecting the importance of the hierarchy that puts prevention and rescue at the top of any FW strategies.

The introduction of the FEW perspective through the energy and water intensity of the valorization makes the framework coherent with the states of the local energy and water systems, within which decision-makers must make decisions. This framework is an important step for a more holistic approach to create strategy for FW.

Yet, the framework does not provide a strict weighting or hierarchy scheme for the valorization options that would reflects precisely the local energy and water system characteristics. Overall the need to further contextualize the framework would be a key next step in its development.

Contextualization of FEW Nexus Insights

In FEW-nexus studies, there is an obvious need to contextualize one's findings. The variety of local and water systems imposes a constant reflection on what the FEW nexus data uncovered through an analysis means in the study's context.

Had Amsterdam been located in a water-scarce region, the findings and the suggestions would have been very different. Putting a focus on water recovery or low-water consumption would have been a logical step in a potential FW valorization strategy. As it was mentioned in Chapter 3, the embedded water lost through its FW is enormous compared to the water use of Amsterdam's residential sector. However, Amsterdam is not located in a stress-prone area regarding water, and the water embedded in the food reaching Amsterdam does not originate from Amsterdam.

A large part of the food consumed probably do come from the Netherlands, therefore there are indeed impacts on the regional energy and water systems surrounding Amsterdam. Yet some food may originate from Europe or even other continents. Taking the case of Europe, Spain imports some food products into the Netherlands, and has known several long droughts over the last decades (Vicente-Serrano et al. 2017). As a result. the production of water-intensive food products for the Dutch market may have an impact on their water system. Therefore, the chosen study's boundaries and the context are crucial parameters in the development of FEW nexus insights.

Thus, the results on the water and energy inputs for the different treatment technologies presented in this study are important indicators for the specific context of Amsterdam. On the other hand, the embedded energy and water in Amsterdam's food flows provide a general indication of the intensity of their resource consumption but ought to further refine for their context-specific impacts.

This could be done through the development of an Environmentally Extended Input-Output Analysis (EEIOA). This method is based on multi-regional input-output models (MRIO) where the production and consumption's effects throughout the global supply chains can be analyzed and their environmental impacts assessed for every country taking part in a specific supply chain (either for production, consumption, or as a trade intermediary).

This method has been recently used for the study of the FEW nexus, connecting domestic consumption to the embedded water, energy, and food from the global supply chains network on which the domestic consumption is based (Owen et al., 2018). Lenzen et al. (2013) used an MRIO model to quantify and localize the use of scarce water throughout the global supply chain and associate its consumption with national consumption of goods while Lan et al. (2016) had a similar approach for the energy footprint of different supply chains. Therefore, such an approach may help understand better the FEW nexus impacts of the food consumption of Amsterdam along the regional and global FSCs feeding the city.

The main issue of these models may be the lack of granularity where most of the supply chain data are quantified at the country-level and therefore assumptions are needed to scale it down to the city-level (Moran et al, 2018).

Along the same topic and as mentioned above, the new FW management and valorization framework suggested in this study does not quantitatively address the context in which it is used. In other words, it is lacking a weighting or adjustments scheme in order to make the assessment of FEW nexus requirements more dynamics by considering the state of the local water and energy systems.

One could imagine a weighting system based on a water scarcity index and energy scarcity index. For example, the FAO has developed a water scarcity index, based on two indicators, the renewable freshwater per day per person (in liters) and the percentage of renewable freshwater withdrawn (FAO, 2014). These two indicators provide a scale to classify countries from “No Water Stress” to “Absolute Water Scarcity” (FAO, 2014). Therefore a city located in a water-stress country could use their ranking on the water scarcity scale as a weighting factor, and inform more precisely the FEW nexus analysis, and the subsequent recommendations in the technologies available to valorize their FW. This aspect of the framework would then be closer to the original purpose of a FEW nexus approach grounded in the concepts of food, energy, and water security (Hoff, 2011; Albrecht et al., 2018).

Nonetheless, this step would then merely consider the physical limitations of the local water and energy systems (i.e. physical scarcity). Yet, there is a second type of limitations that ought to be considered when offering insights from a FEW nexus perspective, which is the political limitations of the local FEW system. This would refer to any policy or local strategy to limit or reduce the use of energy and/or water because they are attempting to reach reduction targets, such as the ones highlighted in the Paris Agreement where nations pledge energy use reduction targets. In this study, the political limitations were an important aspect to substantiate the recommendations of technologies. Indeed, Amsterdam aims to reduce its energy consumption while increasing its renewable production targets (Hoek et al. 2015), making anaerobic digestion one of the most attractive options.

Thus, introducing more explicitly these politically-set limits into the framework would also provide an improved framing and contextualization of the FEW nexus impacts to consider.

Social and Commercial Rescue Initiatives

This study provides a comprehensive overview of the rescue initiatives taking place in Amsterdam and contributes to the nascent field of research on social and commercial rescue initiatives (Corbo & Fraticelli, 2015; Mourad, 2016; Michellini et al., 2018). 12 social and commercial initiatives were assessed, namely Instock, Guerilla Kitchen, Robin Food Kollektief, Taste Before You Waste, BuurtBuik, Oma's Soep, Dumpersterdam, Too Good To Go, Olio, ResQ, NoFoodWaste, and Thuisafgehaald.

First, this study's findings are consistent with Michellini et al. (2018)'s study suggesting that non-profit and social supermarkets model such as Taste Before You Waste or Guerilla Kitchen are not expanding or replicating their model by using online platforms. These social initiatives do not have a true online presence and mostly do reach out to beneficiaries through digital applications, which may limit their reach of new beneficiaries.

Furthermore, this study provides further evidences of the rise of commercially-oriented, sharing-for-money online platforms such as Too Good to Go or ResQ (Michellini et al. 2018).

Additionally, the recent launch of Olio in Amsterdam illustrates also the emergence of the sharing-food-for-community model highlighted by Michellini et al. (2018), which as opposed to social "supermarkets' "initiatives embraces digital platforms and makes sharing free food possible for private individuals, as opposed to the sharing-for-money model.

Furthermore, FW rescue potential framework developed in this study provides six axes of assessment to compare rescue initiatives: *price incentive, user reach, infrastructure and technology needed, ease of use, social impact,* and *FW awareness*. These categories broadly cover the most important aspects of social and commercial initiatives. These categories may be further developed with metrics and indicators and used to perform in-depth studies on social and commercial initiatives.

To date, there are few estimates on the quantity of food rescued through the social and commercial initiatives (Schneider, 2013) and therefore, more work is needed in this area. The rise of online platforms such as Too Good To Go that claims that they will able to save 100,000 meals being thrown away in the year 2020 (Too Good To Go, 2018) is disrupting the status quo in terms of FW rescue potential and ought to be better understood.

Mourad (2016) stated that about 10% of FW were avoided in the US thanks to the work of rescue initiatives, though considering the difference in consumption patterns, legislations, as well as the types of social and commercial initiatives present, this number may be hardly applicable to the European context.

Once estimates are quantified, it would be possible to investigate the relationship between the sheer quantities of FW recovered and the qualitative score in each of the category suggested in this study. This would enable to see if any correlation exists between certain features (e.g., infrastructure needs, user reach) of social and commercial initiatives and their FW rescue abilities.

Additionally, quantifying the specific FW flows reaching these initiatives would enable to understand if these flows meet the demand in terms of volume but also variety. It is often the case that such initiatives are overwhelmed with specific food products, such as bread, but lack other key food items (Schneider, 2013).

Thus, thanks to the quantified FW amounts in Amsterdam and the inventory of these rescue initiatives in Chapter 4, the opportunity to quantify how much FW they recover in practice would provide a richer picture of their role and would therefore be an interesting future study.

Furthermore, an interesting feature of this scoring system is that it ensures that even though the physical rate of FW recovery may be low for a given initiative, their value is still illustrated through their scores in the social impacts they have and their awareness raising capabilities.

As new labels, regulations, and information are frequently produced on FW and other related issues, and the general population has a hard time keeping up (Milne, 2012; Van Boaxstael et al., 2014), these grassroots actors represent a crucial relay for local authorities to educate the public. In addition, the role of these social initiatives goes beyond the sheer rescue of FW, but enables disadvantaged communities to have access to food, contributing to safeguarding their safety and dignity (Michellini et al., 2018).

Lastly, the new FW management and valorization framework developed in Chapter 6 does not address two key issues related to the relationship between rescue initiatives and food prevention strategies.

Firstly, these social and commercial initiatives may be seen as targeting merely the symptoms of food surplus leading to FW in food services, wholesale and retail stores, rather than the structural causes leading to these surplus in the first place (Mourad, 2016). Therefore, FW-producing businesses can use these initiatives as both a CSR opportunity, contributing to their positive public image (Michellini et al., 2018) and as a pretext to neglect achieving structural change in their supply chain management to reduce their current high amounts of FW. However, it can be noted that prevention is still clearly presented as the best option (above FW rescue) within the newly suggested framework.

Secondly, there is an inherent tension between AFW prevention and AFW rescue initiatives. In theory if AFW prevention is achieving its overall goals, little AFW would reach social rescue organizations. This may therefore result in a situation in which disadvantaged communities may not be able to depend as much on these rescue initiatives and may need to find other food sources. For profit-making companies such as Too Good To Go, it is also not clear whether or not the absence of FW production from their food partners, which would compromise their business model, would be considered as a positive outcome. Nonetheless, a complete prevention of AFW in a city like Amsterdam is still substantially far ahead.

Recommendations for the Municipality of Amsterdam

This study produced a multitude of insights on the issue of FW in Amsterdam. Due to the central position of the municipality in the waste management system and its key role to play in a future FW scheme, recommendations derived from these new results are made to support it in the establishment of a FW management and valorization system.

Recommendation n°1: Establish a Clear Distinction between AFW and UFW.

It is important that Amsterdam's municipality integrates early on the notions of AFW and UFW to instruct any policy decision regarding FW. Indeed, two distinct strategies must be put in place by the municipality regarding AFW and UFW. UFW ought to be at the center of the valorization strategies of specific FW streams. On the other hand, all efforts should be put on reducing and preventing as much as possible AFW, whether within the food processing, wholesale, retail, restaurant or hotel sectors.

Therefore, this distinction will nurture and guide the development of both AFW prevention and rescue policies for these sectors *and* FW valorization policies to maximize the resource recovery from Amsterdam's UFW. This distinction enables to distinguish better the tradeoffs and synergies between the three steps presented (i.e., prevention, rescue, valorization) in the FW management and valorization framework.

Recommendation n°2: Focus on Vegetables, Fruits, Potatoes, Coffee Grounds for a Valorization Scheme.

Putting a focus on the recovery of vegetables (including potatoes), fruits, and coffee grounds as starting points of a FW management and valorization framework can help establish a tangible and simple FW system for Amsterdam's households. By focusing on few FW streams, it will avoid cluttering the public message crafted by the municipality. Of course, what is considered as AFW and UFW among those streams should be made explicit. Educating the public on this concept is a challenge, yet by considering only few streams, it will be possible to establish these notions more efficiently across the population.

Recommendation n°3: Consider Anaerobic Digestion, BSF Bioconversion, and Composting as Valorization Options.

Based on the inventory of valorization technologies (cf. Chapter 4) and their preliminary FEW assessment (cf. Chapter 5), it is recommended that the municipality considers an anaerobic digestion plant as a strong option for the treatment and valorization of FW, producing both biogas (helping it to reach its renewables energy targets) and bio-fertilizer (digestate). BSF bioconversion may be a cost-effective option due to the production both compost and insect protein and the lower infrastructure requirements than an AD plant. Composting is also an option, with very low water and energy requirements, though produces less useful outputs.

AEB may be a strong partner in the establishment of these technologies. By focusing on FW flows mentioned in recommendation n°2, these solutions are well-understood and implementable. Focusing on this limited range of technologies does not mean excluding entirely the value-added chemical pathway. This pathway may be further explored thanks to pilot projects, such as the one established by AEB. Yet, as repeatedly mentioned throughout this study, more information is required to understand the FEW nexus impacts of these technologies.

Recommendation n°4: Support Social Food Rescue Initiatives through Ambitious Rescue Policies.

The numerous social initiatives across Amsterdam are important grassroot projects that ought to be supported and expanded to increase the AFW rescue potential of this group of stakeholders. For example, in 2017, France voted a ban on FW waste disposal for retail stores. Such legislations may help further the connection between social initiatives with the wholesale, retail, catering, and restaurant industries.

The groundwork performed by these initiatives to raise awareness about FW, connect AFW to population with low food security, and create a social fabric around FW topics are an asset for the city of Amsterdam. The creation of an organization regrouping these initiatives, while respecting the autonomy of each member, may help create synergies between them, create pools of resources, expand existing and launch new initiatives to tackle the issue of AFW.

Recommendation n°5: Use the Water and Energy Embedded to Educate about the Impacts of the Food Wasted in Amsterdam.

Dietary choices are increasingly considered to have an important influence on the environmental impacts of cities (Springmann et al., 2018; Heard et al., 2017). FW educational campaigns, with focus on the water and energy losses associated with this FW may help put forward the high FEW impacts embedded in the food waste in Amsterdam. Carbon footprint is generally less understood by the general public due to the intangible aspects, far from everyday metrics. Such a framing will also help illustrates that the impacts of the food consumed in Amsterdam extends far beyond its physical boundaries (Heard et al. 2017).

Study's Representativeness

The findings of this study beg the question of whether Amsterdam is a representative city in terms of FW flows, compared to other cities. Does the amount and characteristics of FW produce at the household-level is applicable to other cities? And, does the comparison with businesses located in urban centers still hold with other cities?

Considering the data sources (CREM 2010;2013;2016, Voedingscentrum, 2017; Kantar Public, 2016; REPAIR, 2018; GfK, 2016), which collected data originated from Amsterdam, its surrounding metropolitan area, and the Netherlands, there are strong arguments for the study's FW household model to be applicable with reasonable accuracy to other Dutch cities.

First, comparing the food flows into Amsterdam's households to Vanham et al.'s (2016) estimates, their study found that Amsterdam's residents consumed about 902 kg of food per capita per year. These figures are substantially higher than this study's estimates of about 340 kg per person per year. This may be explained by the fact that Vanham et al. (2016) consider food both consumed within households and the food consumed in restaurants, schools, hospitals, catering services, and other food services. Their data is a top-down estimate using FAO datasets, while the data used in this study are based on bottom-up data acquired through surveying Dutch households (Voedingscentrum, 2017). The CREM 2010 reported about 530 kg of food purchased by the Dutch households they surveyed, though they did not provide an estimate in their subsequent survey campaigns in 2013 and 2016.

Second, comparing the FW flows from households quantified in this study with the REPAIR model, the numbers are matching very closely with the figures of UFW flows and fairly closely with the total AFW figures (12% difference by weight). There are some variations for specific FW flows that may be the results of different calculations methods and assumptions. For example, the REPAIR team did not use exactly the same UFW categories, illustrated by the absences of "meat offal", "fish offal", and "potatoes peels" in their study. These food types may have been integrated in other UFW categories (e.g., other food products; vegetable peeling).

As Vanham et al. (2016) and the REPAIR research group highlighted, there are some variations in terms of waste generation depending on the urbanization level of the municipality. Therefore, it would be possible to adjust the estimates of FW production for municipalities with various urbanization levels thanks to the same method implemented by the REPAIR project, using the same urbanization-level correcting factors (REPAIR, 2018).

Furthermore, the waste streams of FW at the household-level may vary. For example. Amsterdam does not collect GFT while some municipalities do. Therefore, while the total volume and characteristics of FW can be applicable to other cities, their disposal routes may vary substantially. For example, in the case of the REPAIR project, they estimated the share of FW within GFT and residual waste thanks to the CREM surveys (2010;2013; 2016) as it represented the most reliable data for the Amsterdam's metropolitan area.

Third, regarding the production of FW by businesses within an urban area, this study's estimates are mostly based on top-down data. Yet, the literature of the distribution of FW across the entire supply chain in Europe shows substantial variations in the estimates (Corrado & Sala, 2018). This is due to the difficulty to find accurate data and consistent uses of FW definitions (Xue et al., 2017).

The FW-focus European research group FUSIONS estimated that in Europe, households cause 53% of the total FW, followed by the food processing stage with 19%, the food services (12%), the production stage (11%), and finally the wholesale and retail stages (5%) (Stenmarck et al., 2016). The study's findings only considered Amsterdam's strict municipal boundaries, and therefore found households responsible for 87% of the total FW (in tons), 9.6% for the processing sector, 2.2% for the wholesale and retail sectors, 1.2% for the food services sector. The food production sector did not contribute to the city's FW flows as there are no sizeable food production activities taking place in the city. Yet as the FW produced by business is not as defined as for the households' FW flows (i.e., UFW and AFW for each food category), these figures may vary slightly.

Study's General Limitations

There are several uncertainties, limitations, and shortcoming to consider in this study.

First, there are different level of uncertainties presents in this study to discuss.

The data used to quantify the embedded energy and water within each food category considered for Amsterdam's households' FW flows are representative to a European level as the majority of the LCA and water footprint studies are based in a variety of European countries. Therefore, they do not give a precise answer of the energy and water used throughout the food products that reach Amsterdam's households. Rather it merely gives an order of magnitude among the different FW flows, and sketch the energy and water used throughout the FSC. Additionally, there is a small discrepancy relative to the system boundaries of this data. While most data for the embedded energy extent from the production till the food product reach the consumer, the water footprint data covers mainly the production and processing stages of every food type considered in this study. Yet, as most of the energy and water impacts occur at the production stage, it has only a small to moderate influence on the results of the analysis.

In addition, the usual small sample sizes of FW households' studies induce the potential of not having representative estimates for the households. Although in the case of this study, the data from Voedingscentrum (2017), the GfK, CREM, and Kantar Public surveys represent solid FW estimates due to their methodological consistency and frequency over the last decade. Therefore, the uncertainties regarding households' data are moderate. There still no universally adopted FW categorization framework when it comes to assess whether a food type has an unavoidable and avoidable wastable portion, or even the definition of a food type. Therefore, these variables definitions may lead to some discrepancies regarding the quantified food waste categories and their waste status (i.e., AFW or UFW).

Last, there are still relatively high uncertainties when it comes to assessing certain food type wastage (e.g. soup). Self-reported data often underestimates the amount of food waste (Kantar Public, 2017). The quantification of disposal routes, especially for liquid products is still in its infancy in FW studies. Thus, integrating Kantar Public's assessment of these disposal routes is a novel approach chosen in this study that may still add a new layer of uncertainties. As a result, there are still relatively high uncertainties surrounding the avoidable wastage of coffee, tea, soups, and liquid dairy products. For example, it was decided to classify all coffee grounds waste under the unavoidable FW category due to a lack of solid estimate in avoidable coffee waste.

Second, the Companies MFA model, the FEW analysis of the 12 technologies, and the system boundaries chosen in this study present several limitations and shortcomings.

Firstly, as the data for the FW-Companies MFA is produced mostly from top-down data, it reflects an accurate picture of the overall FW production from companies located in Amsterdam. Nonetheless, it may not reflect accurately the efforts performed by individual companies to reduce their FW flows, and on the other hand, it may also hide certain actors that produces a notable amount of FW compared to their size and type of activity. This uncertainty regarding companies' FW production lies in the highly sensitive nature of these types of data (Welink, 2015; REPAIR, 2018). Companies are not keen to communicate on their waste streams. They are wary that this information might reveal some of their industrial processes or put them under public scrutiny if some waste streams are deemed problematic by the general public. This is one of the main reasons why the Companies MFA presents only two highly aggregated FW flows (i.e., 09.1 and 09.2). It was therefore not possible to achieve the level of detail and disaggregation present in the Household MFA.

Secondly, the FEW analysis of the 12 technologies reviewed in Chapter 5 only considered the water and energy process inputs and did not assess the indirect energy and water inputs present in other inputs; e.g., the energy used to produce a solvent useful for extracting value-added chemicals from FW streams. This study also did not take into account the FEW inputs for the infrastructure required for the different technologies.

In addition, although this study outlined the different key actors and strategies in the collection of the targeted FW flows, it does not quantify the energy and water use during the collection step, and for that matter, it does not provide a comprehensive collection strategy for the FW flows of Amsterdam. However, studies and thesis have been published regarding organic waste collection strategies, even specifically for the case of Amsterdam (Teeuwen, 2018).

Finally, the analysis of these technologies did not consider the costs related to the infrastructure construction, operations, and maintenances. Though, it did consider the revenues stemming from the production of useful outputs, such as biogas or compost.

Third, the system boundaries play an important role in this study as it was limited to the physical boundaries of the city of Amsterdam. It is frequent for UFS studies to integrate the surrounding hinterland, establishing therefore a city-region boundaries for the analysis (Wiskerke, 2015). Of course, the region around Amsterdam can play a key role, both in terms of FW-resource exchanges and in terms of connection for the energy and water systems. In addition, the expansion of the system boundaries may change the picture of the largest producers of FW, as many food businesses are located closely outside the city. However, as the system boundaries expand, so does the uncertainties of FW data, the complexity of interactions between the three systems, and the intricacy of stakeholders' networks. As a result, this study provides a granular urban analysis of the FW flows within Amsterdam but does not provide an overview of the potential synergistic connections with Amsterdam's hinterland.

Future Outlook and Research Opportunities for FEW Nexus and FW studies

Where does this study leave the field of FEW Nexus and FW studies? This study contributes to the FEW nexus and the FW research fields in multiples ways. The following paragraphs outline the future outlook for these two fields.

FW studies

First, this study supports the latest developments in the FW field of study. This thesis embraces the overarching strategy suggested by Morone et al. (2019) of minimizing AFW creation and maximizing UFW valorization. This approach is very sensible and enables a richer discussion regarding strategies to tackle FW issues. Thus, future FW studies ought to pursue this conceptual approach in order to generate distinct and complementary strategies for the issues surrounding FW management.

Furthermore, the use of the terms AFW and UFW is progressively gaining momentum in FW studies (Corrado et al. 2017; Beretta et al. 2017; Morone et al. 2019), and this study supports this trend. Corrado et al. (2017) suggested the use of '' possible avoidable FW". Although it would help identify ways to prevent the waste of the fraction of food products located in the grey area between AFW and UFW, it adds another layer of complexity to the analysis while the use of AFW and UFW are still not fully grounded in a universally-accepted definition. Therefore, for now, this study suggests to solely focus on AFW and UFW for future research.

Additionally, the classification of food type should be aligned within the field of FW studies. Whether it is by using the guidelines of the European Category Codes to classify food products (Food Safety Authority of Ireland, 2001) or followed the guidelines of the FAO and the WHO, a commonly-agreed categorization system is required to enable comparison and reduce uncertainties throughout future FW studies.

In addition to a universal categorization of food products, the need to universally defined which parts of food products may be considered unavoidable and avoidable waste will need to be defined to ensure coherence in the FW field.

Last, this study contributes to the emerging research on FW social and commercial initiatives (Corbo & Fraticelli, 2015; Mourad, 2016; Michellini et al., 2018), as mentioned above.

FEW nexus Studies

Second, this study contributes to the advances of knowledge in the field of the FEW nexus.

FEW nexus studies have been characterized by the development and use of diverse frameworks, varying in complexity (Shannak et al., 2018) and different methods of analysis (Albrecht et al., 2018). This trend is unlikely to change in the near future as this body of work evolves and grows. This study; with the use of an MFA, the use of data stemming from LCA and water footprint studies, and the proposition of a new FW framework using a FEW nexus approach; epitomizes the multi-tool and multi-disciplinary nature of this fast-moving field.

LCA is being increasingly established as an important tool to consider for future FEW nexus studies (Mannan et al., 2018; Zhang et al. 2018). Recent studies suggest that this method is now being use explicitly to address the FEW nexus (Walker et al., 2018).

MFA is an important accounting tool, as shown during this study, and therefore its use can support the analysis of variety of FEW nexus issues (Albrecht et al., 2018).

In addition, the use of environmentally-extended input-output analysis (EEIOA) offers promising opportunities for future FEW nexus studies (Owen et al., 2018), where geographic-based supply chains data may show where energy and water are consumed; and therefore observe which countries' energy and water systems are affected by the global trade of food and related commodities. Yet, this tool tends to render observations at the country-level, therefore these results must be downscaled to the regional and city-levels to provide more actionable information, a core feature of FEW studies (Albrecht et al., 2018).

Therefore, there is a need to integrate existing analytical methods so as to develop insights with high-granularity for multi-scale FEW nexus issues.

New Research Pathways

The fields of FEW and FW studies are ripe for innovations and new research pathways thanks to the recent rise in interests in FW valorization, the new development of bio-based technologies, the circular mindset increasingly established by the Circular Economy, and the explosion of FW online platforms and citizen-led initiatives to rescue FW.

First, an interesting research pathway relates to characterizing the FW rescue capacity of social and commercial rescue initiatives, quantifying how much AFW they are currently rescuing and how much these initiatives could *potentially* recover depending on a variety of factors. This is very important considering the recent development in online FW platforms, which can reach an unprecedented number of users (e.g., Too Good To Go).

The qualitative framework developed in this study could be further used to frame and identify what characteristics make FW initiatives successful in recovering large amounts of AFW. It may also be used and refined further to test different characteristics. For example, a study could be performed on the social roles of these initiatives (e.g., social interactions, social inclusion), their awareness raising capabilities and their relation to beneficiaries' behavior change that ultimately induce FW reduction.

Second, a crucial future research pathway will be to quantify and understand better the energy and water requirements, as well, as the environmental performance of the technologies extracting value-added chemicals from FW. As many technologies are still evolving at lab-scale, *exante*-LCA studies could be useful to assess their potential impacts prior to their large-scale deployment. An in-depth state-of-the-art review regarding the energy and water intensities of the latest bio-based processes using FW as a feedstock would therefore be an important step forward in FW studies and the field of bio-based processes.

Third, integrating analytical tools such as EEIOA, MFA, and LCA to develop highly-granular FEW case studies represent a promising future research pathway. This would enable to derive richer insights in the complexity and the required contextualization of the FEW connections and impacts uncovered while performing case studies. Many methodological hurdles remain but promising examples have been recently developed in terms of tools integration (Moran et al., 2015), though not yet in the FEW nexus field.

Recommendation for the FW and FEW nexus fields

Last, five recommendations are suggested to FEW and FW research practitioners to develop and grow their respective research fields.

Recommendation n°1: Integrate the use of the terms avoidable and unavoidable food waste in any FW study and focus on AFW minimization and UFW valorization maximization.

Recommendation n°2: Concentrate efforts on bridging the knowledge gap for the water and energy intensities of bio-valorization processes.

Recommendation n°3: Characterize and quantify the FW flows recovered by social and commercial FW rescue initiatives.

Recommendation n°4: Pursue tools integration to achieve a comprehensive and contextualized FEW nexus overview of the subject studied.

Recommendation n°5: Use and further develop the new food waste management and valorization framework.

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General Conclusion

At the onset of this study, several questions were asked in order to guide the research process. The following paragraphs aim to provide brief answers to these questions. This chapter also aims to answer the main research question of this thesis, namely: *To what extent can the FEW-nexus perspective, combined with the bio-based economy approach, help identify the best options to manage and valorize urban food waste streams?*

Answering the Research Sub-Questions

SQ1: What are the main intersections between the urban FW flows and the FEW-nexus?

The main intersections between FW and the FEW nexus occur during the treatment and valorization of FW. Depending on the technology chosen, FW must be dried, milled, mixed, heated or incinerated resulting in the consumption of energy. FW must also be diluted, washed, dewatered, treated in water solvents, therefore using various amounts of water. Technologies treating FW can also produces useful outputs such as biogas, bio-char, biofuels, or bio-oil for the energy system. Yet, it is also important to understand the connections of these three systems have along the entire FSC. Food products reaching consumers cumulate significant amounts of energy and water consumed along their entire life-cycle. The production stage of the food products' life-cycles represents a major contributor of to the overall cumulative energy and water use in the entire FSC.

SQ2: What are the main food waste flows of Amsterdam?

Amsterdam's households produce the largest amounts of FW in the city, with 65,000 tons per year. The largest avoidable FW flows are *bread, dairy products, vegetables, and fruits* and the largest unavoidable FW are *vegetable peels and husks, fruits peels, coffee grounds,* and *potatoes peels*. FW-producing companies located in Amsterdam produces 6.5 times less FW than households, with the food manufacturing sector as the largest producer of FW among the different food sectors.

SQ3: How much embedded energy and water are present in Amsterdam's FW flows?

The embedded energy within Amsterdam Avoidable FW flows was quantified to be 0.51 PJ/year, while the embedded water was quantified to be 58.3 million m3/year. The former represents 15% of Amsterdam's households annual residential electricity consumption, while the latter represent 1.45 times the total volume of water consumed within Amsterdam's households.

SQ4: What are the initiatives and technologies available to valorize urban food waste products?

There are four main strategies for the valorization urban FW, namely energy valorization, value-added chemicals extraction, bio-material, and feed. Energy valorization includes technologies and processes such as anaerobic digestion, incineration, pyrolysis, or biofuel production. Value-added chemicals extraction processes from FW substrates can recover among others valuable chemicals: phenol, pectin, furfural, and essential oils. The biomaterial strategic cluster includes bio-polymer, bio-fertilizer, enzyme, and bio-adsorbent. The feed cluster contain animal and protein feeds.

The initiatives available to rescue FW range from *social initiatives*; such as social supermarkets, social restaurants, social educational events and workshops, neighborhood FW dinners; to *commercial initiatives*; such as a variety of online platforms where soon-to-be-wasted food can be bought for discounted price or exchanged for free.

SQ5: What are the best options to recover FW from a FEW nexus perspective?

In the context of Amsterdam, anaerobic digestion, Black Soldier Fly bioconversion, and composting appear as the most FEW-efficient technologies for the Dutch capital. Anaerobic digestion is promising due to its renewable energy production, which is in line with the renewable energy objectives of Amsterdam. The dense constellation of social and commercial FW rescue initiatives represents an important asset to rescue avoidable food waste and limit the wasting of FW's embedded water and energy.

SQ6: What advantages and limitations have been encountered by applying the FEW nexus approach to the urban food waste issue?

The use of the FEW nexus approach enables to comprehend the important amounts of energy and water embedded in the food consumed within cities, showed which food products have a high energy and water requirements, provided an insightful way to assess FW treatment and valorization technologies; especially highlighting the little knowledge available on the energy and water intensities of value-added chemical extraction processes.

The FEW nexus limitations include neglecting other environmental impacts due to a sole focus on the energy and water impacts of FW, the lack of a comprehensive framing of stakeholder and governance processes, and the lack of a strong communication strategy related to the FEW nexus findings.

Final Remarks

The municipality of Amsterdam has an ambitious vision to become a sustainable metropolis, increasing its share in renewables energy, reducing its energy use, and actively trying to pursue circular economy policies (Hoek et al., 2015). AEB, Amsterdam's WtE plant, epitomizes this will by relentlessly searching for new ways to create value out of its waste streams and transforming itself in a provider of sustainable energy. Despite the municipality's ambitions, Amsterdam does not have currently a coherent and innovative program regarding its FW streams. The municipality is therefore interested in defining a strategy for its FW streams (Gemeente Amsterdam, 2018).

In conclusion, the use of the FEW nexus perspective combined with the bio-based economy approach was fruitful in developing numerous and varied insights into Amsterdam's FW flows. Specifically, it provided valuable insights into the best strategies available, both in terms of prevention and rescue of avoidable food waste and the valorization of unavoidable food waste. As for any approach, some limitations and shortcomings were identified. Nonetheless, the FEW nexus perspective and the bio-based economy approach have been instrumental in advancing knowledge in the field of food waste studies.

The municipality of Amsterdam has set itself onto an ambitious path both in terms of sustainability and the circular economy. A comprehensive food waste strategy for the city is therefore a coherent next step aligned with the future envisioned by the municipality. This study provides key information and strategies to facilitate the implementation of a future food waste management and valorization scheme for the city of Amsterdam.

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Appendices

Table A1: Composition of FW from Residual Household Waste from CREM (2016)		
Unavoidable Food Waste (UAFW)		
Code	Food Type	Weight % from total UAFW in Household Residual Waste
UA10.83.1	Coffee grounds	31.63%
UA1.2	Fruits	26.21%
UA1.13	Vegetables (incl. melons, roots & tubers)	26.20%
UA10	Other Food products	10.99%
UA01.47.2	Eggs shell, fresh	2.40%
UA10.83.1	Tea grounds	2.30%
UA10.5.1.4.	Cheese crust	0.31%
Avoidable Food Waste (AFW)		
Code	Food Type	% by weight from total AFW in Residual Stream
A10.7.1	Fresh bread	20.12%
A11.3	Vegetables (incl. melons, roots & tubers)	14.65%
A12.0	Fruits	11.09%
A10.1	Processed meat & meat products	8.82%
A01.4.7.2	Dairy products	7.81%
A10.7.3	Macaroni, noodles, couscous and similar farinaceous products	6.44%
A10.6.1.1	Rice, semi- or wholly milled, or husked or broken	6.12%
A011.35.1	Potatoes	5.72%
A10.8	Other food products	4.79%
A10.7.2.1	Rusks and biscuits; preserved pastry goods and cakes	4.14%
A10.8.4	Condiments and seasonings	3.74%
A10.8.2.2	Chocolate and sweets	2.45%
A10.5.1.4.	Cheese & curd	2.34%
A10.51	Eggs	0.65%
A10.8.9.1	Soups and broths and preparations thereof	0.65%
A10.5.1.4	Processed fish, crustaceans & mollusks	0.47%

Table A2- Embedded Energy in each Food Type
(Adapted and Modified from Tom et al., 2016, Supplementary Information)

Food Product	MJ/kg	Location	LCA Boundary	Author		
1-Fresh bread					Type	Average (MJ/kg)
					Wheat Bread	6.17
Wheat bread, conventional farming	5	Germany	Farm to fork	Braschkat et al, 2003		
Wheat bread, conventional farming	6	Germany	Farm to fork	Braschkat et al, 2003		
Wheat bread, conventional farming	8	Germany	Farm to fork	Braschkat et al, 2003		
Wheat bread, conventional farming	9	Germany	Farm to fork	Braschkat et al, 2003		
Wheat bread, organic	4	Germany	Farm to fork	Braschkat et al, 2003		
Wheat bread, organic	5	Germany	Farm to fork	Braschkat et al, 2003		
2-Macaroni, noodles, couscous and similar farinaceous products					Type	Average (MJ/kg)
Wheat flour	5	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Pasta, Couscous, flour-based products	5.00
Couscous (durum wheat), cooked on a hot plate	5	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
3- Rice, semi- or wholly milled, or husked or broken					Type	Average (MJ/kg)
Rice	10	Sweden	Farm to fork	Carlsson-Kanyama, 1998	Rice	8.5

Rice, cooked as one portion	7	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003		
4-Rusks and biscuits; preserved pastry goods and cakes					Type	Average (MJ/kg)
Rye flour	5	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Muesli	16.00
Cereal, baked	37	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Rye Product	5.00
Cereal, baked	38	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Cereal Products	37.00
Barley, winter	2	Europe	Farm to farm gate	Foster et al, 2006	Oats Products	7.00
Oat flakes	11	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Biscuits	18.00
Oat flake porridge, cooked	3	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Total	16.60
Crackers	18	UK	Farm to fork	Kostantas et al. 2017		
Biscuits (semi-sweet)	18	UK	Farm to fork	Kostantas et al. 2017		
Biscuits (low-fat)	17	UK	Farm to fork	Kostantas et al. 2017		
Muesli (raw rolled oats) with sun dried apples	15	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Muesli (raw rolled aots) with sun dried raisins	17	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
5-Fruits					Type	Average (MJ/kg)
Oranges, fresh	7	Southern Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Orange	7.33

Oranges, fresh	9	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003	Apple	6.40
					Bananas	12.00
Oranges, fresh	6	Brazil	Farm to farm gate	Coltro et al, 2009	Blueberries	9
Apples, fresh	4	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Grapes	9
Apples, fresh	5	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Cherries	7
Apples, fresh	9	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003	Raspberries	9
Apples, locally gown	6	Germany	Farm to consumer home	Blanke and Burdick, 2005	Strawberries	10
Apples, imported, transported by sea	8	New Zealand	Farm to consumer home	Blanke and Burdick, 2005	Kiwi	12.00
Bananas, fresh	12	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003	Mango	12.00
Blueberries	9	Northern Italy	Farm to consumer	Girgenti et al, 2013	Total	9.3733
Blueberries	9	Northern Italy	Farm to consumer	Peano et al, 2015		
Cherries, fresh	5	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Cherries, fresh	6	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
Cherries, fresh	10	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003		
Grapes, fresh	8	Southern Europe	Farm to fork	Carlsson-Kanyama et al, 2003		

Grapes, fresh	10	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003		
Raspberries	9	Northern Italy	Pre-farm to retailer gate	Girgenti et al, 2013		
Raspberries, fresh	8	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
Raspberries	9	Northern Italy	Farm to retailer gate	Peano et al, 2015		
Strawberries, fresh	6	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Strawberries, fresh	9	Southern Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
Strawberries	15	Northern Italy	Farm to retailer gate	Peano et al, 2015		
6-Vegetables					Type	Averag e (MJ/kg)
Bell peppers	18	Italy	Farm to consumer	Cellura et al, 2012	Bell Peppers	18
Broccoli	39	Spain	Farm to grave	Canals et al, 2008	Broccoli	35.875
Broccoli	39	Spain	Farm to grave	Canals et al, 2008	Cabbage	4.5
Broccoli	42	Spain	Farm to grave	Canals et al, 2008	Carrot	2.83
Broccoli	41	Spain	Farm to grave	Canals et al, 2008	Lettuce	9
Broccoli	32	UK	Farm to grave	Canals et al, 2008	Mushroom	4.5
Broccoli	32	UK	Farm to grave	Canals et al, 2008	Onions	3.5
Broccoli	31	UK	Farm to grave	Canals et al, 2008	Melons	24
Broccoli	31	UK	Farm to grave	Canals et al, 2008	Snap beans	21
Cabbage	4	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Tomatoes	52.1

Cabbage	5	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Beans	9.8
Carrots	3	Sweden	Farm to retailer gate	Carlsson-Kanyama, 1998	Peas (frozen)	11
Carrots, fresh	3	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Vegetable Canned	18
Carrots, fresh	4	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Total	16.47
Carrots, organic	1	South Savo	Farm to retail	Raghu, 2014		
Carrots, conventional	2	South-Savo	Farm to retail	Raghu, 2014		
Carrots, conventional	4	Overseas	Farm to retail	Raghu, 2014		
Lettuce	10	Spain	Farm to grave	Canals et al, 2008		
Lettuce	10	Spain	Farm to grave	Canals et al, 2008		
Lettuce	11	UK	Farm to grave	Canals et al, 2008		
Lettuce	8	UK	Farm to grave	Canals et al, 2008		
Lettuce	7	UK	Farm to grave	Canals et al, 2008		
Lettuce	8	UK	Farm to grave	Canals et al, 2008		
Mushrooms	5	Thailand	Farm to farm gate	Ueawiwatsaku et al, 2014		
Mushrooms	4	Thailand	Farm to farm gate	Ueawiwatsaku et al, 2014		
Onions	3	New Zealand to UK	Farm to processing	Saunders and Barber, 2008		
Onions	4	UK	Farm to farm gate	Saunders and Barber, 2008		
Cantaloupe (Melon)	24	Italy	Farm to consumer	Cellura et al, 2012		

Honeydew (Melon)	24	Italy	Farm to consumer	Cellura et al, 2012	
Snap beans	22	UK	Farm to grave	Canals et al, 2008	
Snap beans	20	UK	Farm to grave	Canals et al, 2008	
Tomatoes	42	Sweden	Farm to retailer gate	Carlsson-Kanyama, 1998	
Tomatoes	130	UK	Farm to farm gate	Williams et al, 2006	
Tomatoes	96	Northern Italy	Greenhouse to retailer	Almeida et al, 2014	
Tomatoes	64	Northern Italy	Greenhouse to retailer	Almeida et al, 2014	
Tomatoes	35	Northern Italy	Greenhouse to retailer	Almeida et al, 2014	
Tomatoes	44	Northern Italy	Greenhouse to retailer	Almeida et al, 2014	
Tomatoes, fresh, greenhouse	66	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	
Tomatoes, fresh	5	Southern Europe	Farm to fork	Carlsson-Kanyama et al, 2003	
Tomatoes	16	Italy	Farm to consumer	Cellura et al, 2012	
Cherry tomatoes	23	Italy	Farm to consumer	Cellura et al, 2012	
Vegetables, canned	18	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003	
Brown beans, cooked	9	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	
Brown beans, cooked	11	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003	
Soya beans, cooked	8	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003	

Yellow peas, cooked	5	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Beans, canned	16	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003		
Peas, frozen	10	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Peas, frozen	12	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
7-Potatoes					Type	Average (MJ/kg)
Potatoes	1	UK	Farm to farm gate	Williams et al, 2006	Potatoes	4.2
Potatoes	4	Sweden	Farm to fork	Mattsson and Wallen, 2003		
Potatoes	5	Sweden	Farm to fork	Foster et al, 2006		
Potatoes, cooked	5	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Potatoes, mashed powder, cooked	6	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
8-Dairy					Type	Average (MJ/kg)
Milk, semi-skimmed	5	Netherlands	Farm to grave	Broekema and Kramer, 2014	Milk	6.5
Milk, semi-skimmed	8	Netherlands	Farm to grave	Broekema and Kramer, 2014	Cream	19
Yogurt	13	United States/Europe	Farm to fork	Foster et al, 2006	Butter	35

Yogurt, small pots	11	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Yogurt	12
Cream, 40% fat	19	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Ice Cream	4.5
Ice Cream	4	Europe	Farm to fork	Foster et al, 2006	Total	15.4
Ice Cream	5	Europe	Farm to fork	Foster et al, 2006		
Butter	42	UK	Farm to distribution center	Nilsson et al, 2010		
Butter	30	Germany	Farm to distribution center	Nilsson et al, 2010		
Butter	32	France	Farm to distribution center	Nilsson et al, 2010		
9-Cheese					Type	Average (MJ/kg)
Cheese, semi-mature	29	Netherlands	Farm to grave	Broekema and Kramer, 2014	Cheese	53
Cheese, semi-mature	48	Netherlands	Farm to grave	Broekema and Kramer, 2014		
Cheese	60	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Cheese	64	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
Cheese	65	Southern Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
10-Processed Meat and Meat Products					Type	Average

						(MJ/kg)
Beef	28	UK	Farm to farm gate	Williams et al, 2006	Beef	44.6
Beef, fresh, cooked	70	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Pork	33.429
Beef, frozen, cooked	75	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Poultry	30.455
Cow, fresh, cooked	26	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Lamb	35.222
Beef stew, cooked	24	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Total	36
Pork	39	Sweden	Farm to fork	Cederberg, 2003		
Pork	17	UK	Farm to farm gate	Williams et al, 2006		
Pork, fresh, cooked	40	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Pork, frozen, cooked	43	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Pork, frozen, cooked	44	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
Pork sausage, fresh, cooked	34	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Pork stew, cooked	17	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Poultry	20	Brazil	Farm to farm gate	Spies, 2003		
Chicken, standard	25	UK	Farm to farm gate	Leinonen et al, 2012		
Chicken, free-range	26	UK	Farm to farm gate	Leinonen et al, 2012		
Chicken, organic	40	UK	Farm to farm gate	Leinonen et al, 2012		

Poultry	30	France	Farm to slaughterhouse gate	Prudêncio da Silva et al, 2014		
Poultry	46	France	Farm to slaughterhouse gate	Prudêncio da Silva et al, 2014		
Chicken, fresh, cooked	35	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Chicken, frozen, cooked	39	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Chicken, frozen, cooked	41	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003		
Chicken sausage, fresh, cooked	20	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Chicken stew, cooked	13	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Lamb	32	Europe	Farm to fork	Williams et al, 2006, Carlsson-Kanyama and Faist, 2000		
Lamb	39	Europe	Farm to fork	Williams et al, 2006, Carlsson-Kanyama and Faist, 2000		
Lamb, fresh, cooked	43	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Lamb, frozen, cooked	46	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Lamb, frozen, cooked	52	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003		

Lamb sausage, fresh, cooked	30	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Lamb stew, cooked	18	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
Lamb	11	New Zealand to UK	Farm to processing	Saunders and Barber, 2008		
Lamb	46	UK	Farm to farm gate	Saunders and Barber, 2009		
11-Seafood and Fish Products					Type	Average (MJ/kg)
Cod	60	Europe	Farm to fork	Foster et al, 2006	Cod	53.4
Cod	83	Europe	Farm to fork	Foster et al, 2006	Salmon	46.667
Cod, frozen	58	Norway	Farm to retail	Svanes et al, 2011	Mackerel	37
Cod, frozen	39	Norway	Farm to retail	Svanes et al, 2011	Shrimp/Prawn	31
Cod burger, frozen	27	Norway	Farm to consumer	Svanes et al, 2011	Herring	22
Salmon	58	Europe	Farm to fork	Foster et al, 2006	Tuna (canned)	44
Salmon, farmed, cooked	84	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Mussels/Clams	14.333
Salmon	26	Norway	Farm to milling gate	Pelletier et al, 2009	Sardines	27.333
Salmon	48	UK	Farm to milling gate	Pelletier et al, 2009	Sea Bass	55
Salmon	31	Canada	Farm to milling gate	Pelletier et al, 2009	Trout	78
Salmon	33	Chile	Farm to milling gate	Pelletier et al, 2009	Total	40.873
Herring, fresh, cooked	22	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		

Mackerel, fresh, cooked	37	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	
Prawns	18	Denmark	Fishery to fishery gate	Thrane, 2004	
Prawns	30	Denmark	Fishery to fishery gate	Thrane, 2004	
Prawns	26	Denmark	Fishery to fishery gate	Thrane, 2004	
Shrmp	35	Denmark	Fishery to fishery gate	Thrane, 2004	
Shrimp	42	Denmark	Fishery to fishery gate	Thrane, 2004	
Shrimp	35	Denmark	Fishery to fishery gate	Thrane, 2004	
Mussels	8	Denmark	Fishery to consumer	Thrane, 2004 and Iribarren et al, 2010	
Mussels	11	Denmark	Fishery to consumer	Thrane, 2004 and Iribarren et al, 2010	
Mussels	8	Denmark	Fishery to consumer	Thrane, 2004 and Iribarren et al, 2010	
Mussels	19	Denmark	Fishery to consumer	Thrane, 2004 and Iribarren et al, 2010	
Mussels	21	Denmark	Fishery to consumer	Thrane, 2004 and Iribarren et al, 2010	
Mussels	19	Denmark	Fishery to consumer	Thrane, 2004 and Iribarren et al, 2010	
Sardines, fresh	13	Portugal	Farm to processing gate	Almeida et al, 2015	
Sardines, frozen	17	Portugal	Farm to processing gate	Almeida et al, 2015	

Sardines, canned	52	Portugal	Farm to processing gate	Almeida et al, 2015		
Trout	78	France	Farm to farm gate	Aubin et al, 2009		
Sea bass	55	Greece	Farm to farm gate	Aubin et al, 2009		
Tuna, canned	44	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003		
12-Eggs					Type	Average (MJ/kg)
Eggs	5	United States	Farm to processing facility gate	Pelletier et al, 2013	Egg	5
Eggs, cooked	18	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003		
13-Chocolate and sugar confectionery					Type	Average (MJ/kg)
Candies	18	Sweden	Farm to fork	Carlsson-Kanyama et al, 2003	Total	23.9
Biscuits (vanilla, chocolate-coated, semi-sweet)	20	UK	Farm to fork	Kostantas et al. 2017		
Chocolate	33.7	UK	Farm to fork	Kostantas et al. 2018		
Condiments and seasonings					Type	Average (MJ/kg)
Rape seed oil	15	Central Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Olive oil	24
Rape seed oil	5	UK	Farm to farm gate	Williams et al, 2006	Rape Seed Oil	10

Sunflower oil	20	Overseas	Farm to fork	Carlsson-Kanyama et al, 2003	Sunflower	20
Olive oil	24	Southern Europe	Farm to fork	Carlsson-Kanyama et al, 2003	Total	18
Coffee					Type	Average (MJ/kg)
Coffee	54	Japan	Farm to fork	Hassard et al. (2014)	Coffee	54
Tea					Type	Average (MJ/kg)
Tea	129	Sri Lanka	Farm to fork	Munasinghe et al. 2017	Tea	129
Soups and broth					Type	Average (MJ/kg)
Average (Vegetable/Meat)						25
Other food product					Type	Average (MJ/kg)
Average (All food type except coffee and tea)						21.7

Food Purchased at Retail Store		Amoun	Unit
## Processed meat and meat products	1	24737.42	ton
## Processed and preserved fish, crustaceans and molluscs	1	2803.322	ton
## Cheese and cheese crust	1	7383.344	ton
## Dairy and cheese products	1	68253.31	ton
## Eggs	1	4087.546	ton
## Vegetables (incl. melons, roots & tubers)	1	33916.41	ton
## Fruits	1	32999.64	ton
## Potatoes	1	17960.2	ton
## Fresh bread	1	25165.5	ton
## Rusks and biscuits; preserved pastry goods and cakes	1	2087.338	ton
## Rice, semi- or wholly milled, or husked or broken	1	3148.055	ton
## Macaroni, noodles, couscous and similar farinaceous products	1	12512.66	ton
## Chocolate and sugar confectionery	1	12429.32	ton
## Sauces and fats	1	8201.61	ton
## Soups & broths	1	2719.98	ton
## Other food product	1	16979.04	ton
## Coffee	1	6898.217	ton
## Tea	1	519.2207	ton

# Household		Amoun	Unit
# Unavoidable Food Waste	1	31090.47	ton
## Meat Offals (Carilage, fats, strips)	1	1205.562	ton
## Fish Offals and Seafood shells	1	690.426	ton
## Cheese Crust	1	29.63766	ton
## Dairy and other cheese products	1	0	ton
## Eggs in shell	1	345.6606	ton
## Vegetables Husks and Peels	1	8913.806	ton
## Fruits Peels	1	8653.678	ton
## Potatoes Peels	1	3681.327	ton
## Other Food Products (include other food product category	1	152.9333	
## Coffee ground (dry weight)	1	6898.217	ton
## Tea grounds (dry weight)	1	519.2207	ton
# Avoidable Food Waste	1	34003.54	ton
## Processed Meat and Meat Products	1	2400.25	ton
## Processed and Preserved Fish, Crustaceans and Molluscs	1	150.0156	ton
## Cheese and Curd	1	625.065	ton
## Dairy and cheese products	1	5675.59	ton
## Eggs in shell	1	183.3524	ton
## Vegetables (incl. melons, roots & tubers)	1	4725.491	ton
## Fruits	1	4017.084	ton
## Potatoes	1	2041.879	ton
## Fresh bread	1	7625.793	ton
## Rusks and biscuits; preserved pastry goods and cakes	1	708.407	ton
## Rice, semi- or wholly milled, or husked or broken	1	733.4096	ton
## Macaroni, noodles, couscous and similar farinaceous prod	1	575.0598	ton
## Chocolate and sugar confectionery	1	1333.472	ton
## Condiments and seasonings	1	1400.146	ton
## Soups and broths and preparations thereof	1	775.0806	ton
## Other food products	1	1033.441	ton

Food Waste to		Amoun	Unit
# Food Waste to Waste Treatment	1	65094	ton
> Unavoidable Food Waste	1	31090	ton
> Avoidable Food Waste	1	34004	ton

Figure A1: Households MFA Excel Results

# 10.1-Meat and Poultry Products Manufacturing (12 Companies)	**1**	**1573**	**ton**
## 10.1- FW 09.1	1	1457	ton
## 10.1- FW 09.2	1	117	ton
# 10.2-Fish and Seafood Products Manufacturing (2 Companies)	**1**	**271**	**ton**
## 10.2-FW 09.1	1	271	ton
## 10.2- FW 09.2	1	0	ton
# 10.3- Vegetables and Fruits Processing (3 Companies)	**1**	**313**	**ton**
## 10.3- FW 09.1	1	27	ton
## 10.3- FW 09.2	1	287	ton
			ton
# 10.4- Oils and Fats Products Manufacturing (3 Companies)	**1**	**1332**	**ton**
## 10.4- FW 09.1	1	1016	ton
## 10.4- FW 09.2	1	316	ton
# 10.5- Ice Cream and Dairy Products Manufacturing (4 Companies)	**1**	**87**	**ton**
## 10.5- FW 09.1	1	85	ton
## 10.5- FW 09.2	1	2	ton
# 10.7- Bakery and Farineous Products Manufacturing (167 Companies)	**1**	**2140**	**ton**
## 10.7- FW 09.1	1	65	ton
## 10.7- FW 09.2	1	2075	ton
# 10.8- Other Food Product Manufacturing (33 Companies)	**1**	**1086**	**ton**
## 10.8- FW 09.1	1	273	ton
## 10.8- FW 09.2	1	813	ton
# 11- Beverage Manufacturing (23 Companies)	**1**	**398**	**ton**
## 11- FW 09.1	1	0	ton
## 11- FW 09.2	1	398	ton
# 46- Wholesale Retail (755 Companies)	**1**	**905**	**ton**
## 46- FW 09.1	1	255	ton
## 46- FW 09.2	1	649	ton
# 47- Retail Stores (1017 Companies)	**1**	**682**	**ton**
## 47- FW 09.1	1	581	ton
## 47- FW 09.2	1	101	ton
# 55- Hospitality Sector (520 Companies)	**1**	**638**	**ton**
## 55- FW 09.1	1	523	ton
## 55- FW 09.2	1	115	ton
# 56- Food and Beverages Services/Restaurants (3265 Companies)	**1**	**178**	**ton**
## 56- FW 09.1	1	141	ton
## 56- FW 09.2	1	36	ton

# Residual Commercial Waste Collection		**4808**	**ton**
> 10.1- FW 09.1	1	1457	ton
> 10.2- FW 09.1	1	271	ton
> 10.3- FW 09.1	1	27	ton
> 10.4- FW 09.1	1	1016	ton
> 10.5- FW 09.1	1	85	ton
> 10.7- FW 09.1	1	65	ton
> 10.8- FW 09.1	1	273	ton
> 11- FW 09.1	1	0	ton
> 46- FW 09.1	1	255	ton
> 47- FW 09.1	1	255	ton
> 55- FW 09.1	1	581	ton
> 56- FW 09.1	1	523	ton

# Organic Commercial Waste Collection		**4909**	**ton**
> 10.1- FW 09.2	1	117	ton
> 10.2- FW 09.2	1	0	ton
> 10.3- FW 09.2	1	287	ton
> 10.4- FW 09.2	1	316	ton
> 10.5- FW 09.2	1	2	ton
> 10.7- FW 09.2	1	2075	ton
> 10.8- FW 09.2	1	813	ton
> 11- FW 09.2	1	398	ton
> 46- FW 09.2	1	649	ton
> 47- FW 09.2	1	101	ton
> 55- FW 09.2	1	115	ton
> 56- FW 09.2	1	36	ton

# Waste Treatment Plants	**1**	**9717**	**ton**
> Residual Commercial Waste Collection	1	4808	ton
> Organic Commercial Waste Collection	1	4909	ton

Figure A2: Companies MFA Excel Results

Table A3: Summary of FW Rescue Potential Score Breakdown for each Rescue Initiative - the weighting factors are directly applied in this table (wf. x)							
Weighted Score / Initiatives	**Users Reach (2x)**	**Price Incentive (1x)**	**Infrastructure & Technology Needed (1x)**	**Ease of Use (1x)**	**Social Impact (0.5x)**	**FW Awareness (0.5x)**	**Total (Aggregated) Score**
Instock	4	0	0	3	1	2	10
Guerrilla Kitchen	2	3	2	1	1.25	1	10.25
Robin Food Kollektief	2	1	2	1	1.25	1.5	8.75
Taste Before You Waste	2	3	2	2	2	1.5	12.5
BuurtBuik	2	4	2	2	1.5	0.5	12
Oma's Soep	4	0	1	2	2	0.5	9.5
Dumpersterdam	0	4	4	0	0	0.25	8.25
To Good To Go	8	2	3	2	0	0.5	15.5
Olio	8	4	3	4	1	0.5	20.5
ResQ	8	2	3	4	0.5	0.5	18
NoFoodWasted	6	1	3	1	0	0.5	11.5
Thuisafgehaald	6	0	2.5	2	0.5	0	11

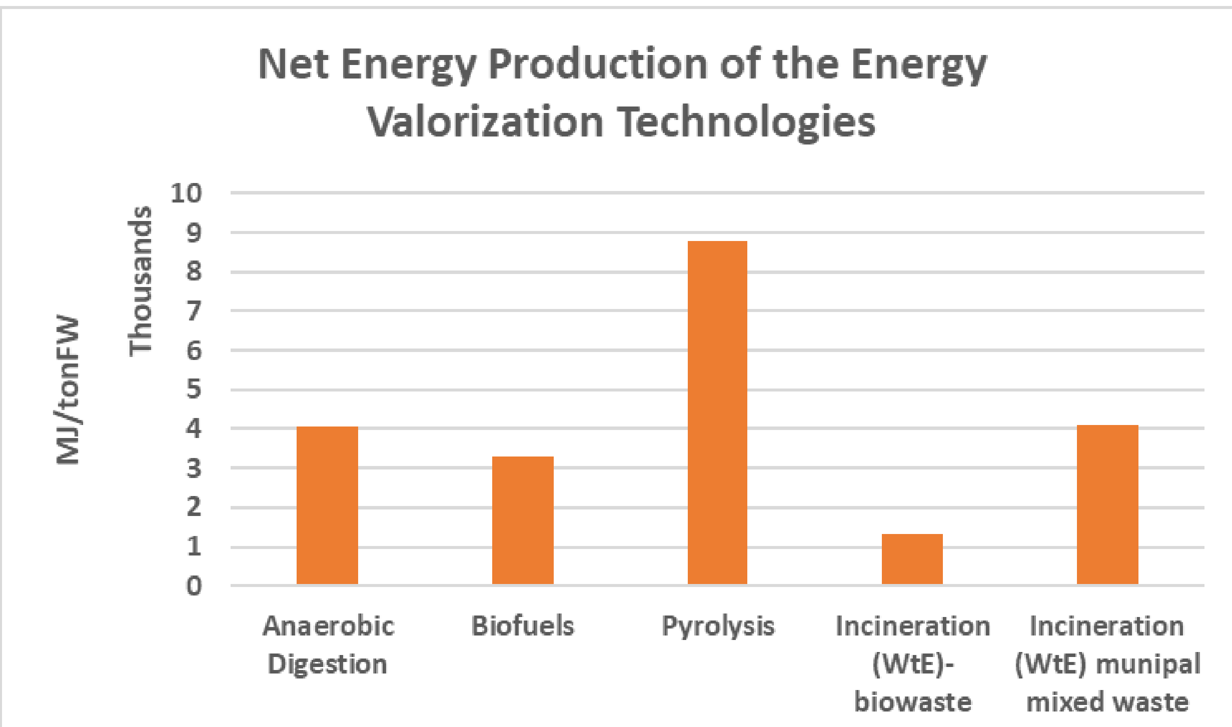

Figure A3: Net Energy Production (Energy Output – Energy Input) for the 5 technologies from the energy cluster assessed in this study.

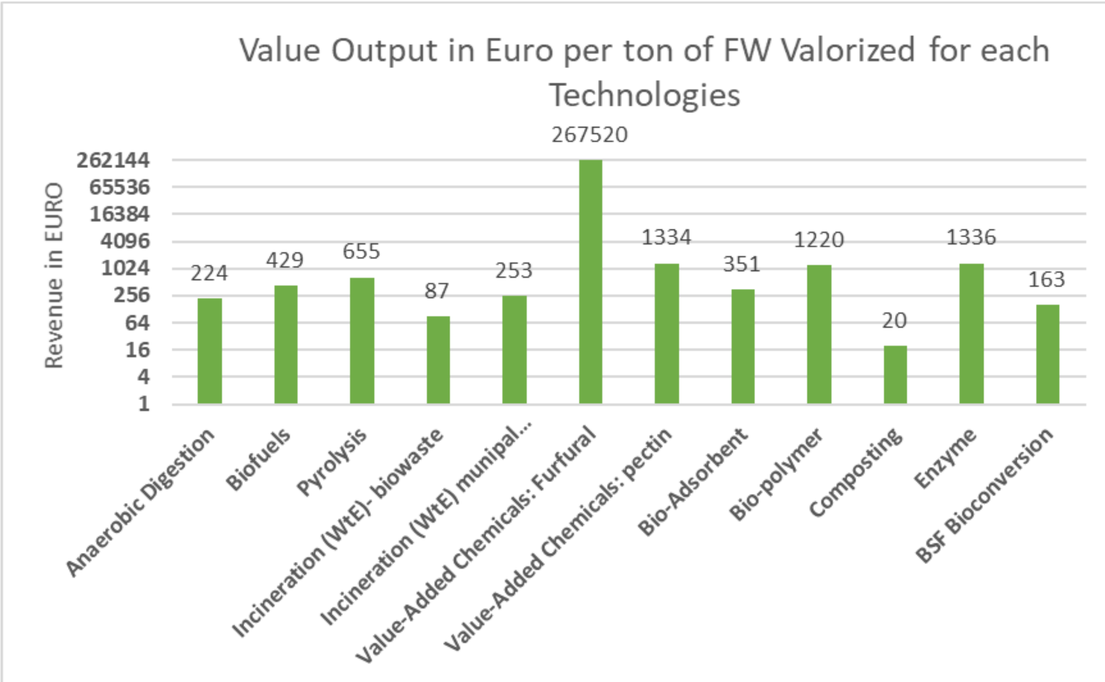

Figure A4: Potential Revenues from the Sale of Products Recovered from Valorizing 1 ton of FW

Table A4: Energy and Water Input Costs			
Product	**Amount**	**Unit**	**Source**
Electricity	0.065	€/kWh	Jungbluth & Chudacoff (2007)
District Heating	0.08	€/MJ	Jungbluth & Chudacoff (2007)
Diesel costs	1.45	€/l	Auto Traveler, 2019
Water costs	1.41	€/l	Average all water providers in NL (Statistica, 2018)

Table A5:Dutch Water Supplier Costs -Data compiled by Statista (2019)		
Water Supplier	**Price**	**Unit**
PWN	1.76	€/l
Dunea	1.65	€/l
Evides	1.61	€/l
WML	1.56	€/l
Waternet	1.55	€/l
Oasen	1.49	€/l
Brabant Water	1.18	€/l
Waterleidingmaatschappij Drenthe	1.16	€/l
Waterbedrijf Groningen	1.15	€/l
Vitens	1.03	€/l

Table A6: Energy and Water Inputs Costs Breakdown (Based on prices in Table A3)												
Technology	**AD**	**Biofuels**	**Pyrolysis**	**Incineration (WtE)-biowaste**	**Incineration (WtE) munipal mixed waste**	**Value-Added Chemicals: Furfural**	**Value-Added Chemicals: pectin**	**Bio-Adsorbent**	**Bio-polymer**	**Composting**	**Enzyme**	**BSF Bioconversion**
Biomass input (t)	1	1	1	1	1	1	1	1	1	1	1	1
Energy Input (normalized-1tonFW)-electricity (kwh)	2	122	114	0	0	123000	6429	90	605	1	1511	68
Energy Input (normalized-1tonFW)-heat (MJ)	242	4150	0	100	131	0	0	0	8190	3	1983	0
Direct Energy Input Costs (sum) (€)	19	340	7	8	10	7995	418	6	694	0	257	4
Water Input (normalized-1tonFW) (m3)	0	1	2	1	1	10	1	0	44	0	0	0
Direct Water Input costs (€)	0	2	4	1	2	14	1	0	62	0	0	0
Total water and energy costs (€)	20	342	11	9	12	8009	419	6	756	0	257	5