Increasing the Circularity of the Floating Farm

A Quantitative Assessment and Advice

Andie M. Kaess

Delft University of Technology

TU Delft

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by

Andie M. Kaess

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Thesis committee:	Dr. M. Palmeros Parada,	TU Delft, Supervisor Sanitary Engineering
	Dr. J. Posada Dunque,	TU Delft, Biotechnology
	Dr. S.J. Smith	TU Delft, Sanitary Engineering

TU Delft

Preface

I would like to express my gratitude to my entire graduation committee physically at TU Delft and the larger committee from Water Mining in the Netherlands, Spain, and the UK for allowing me to research such a unique and innovative topic. This thesis allowed me to utilize skills gained throughout my master's and learn about circularity assessment, circular farming, and how environmental engineering is used in these contexts. This thesis was fulfilling and I can already see how such analyses can help the Floating Farm become more circular.

I want to acknowledge my committee chair and daily supervisor Dr. Mar Palmeros Parada for her consistent support, advice, and enthusiasm which have made my thesis smooth sailing and productive. I would also like to thank Dr. Sanne Smith for her friendly support and for offering a slightly different perspective on the committee with her advice and feedback. Moreover, I would like to thank Dr. John Posada Dunque for his great feedback and willingness to help. From Water Mining and Biotechnology at TU Delft, I would like to also acknowledge Dr. Daniel Dias, Dr. Gonzalo Gamboa, and Akemi Kokubo Roche for their helpful feedback and willingness to help throughout my thesis.

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Abstract

With population increases, the traditional linear economy has become increasingly unsustainable creating environmental pressures such as climate change and resource scarcity. The Dutch government has set lofty goals to create a circular economy by 2050. The agricultural sector in the Netherlands is vulnerable to climate pressures but is also highly profitable at the cost of sustainability making circular models difficult to implement. The world's first Floating Farm in Rotterdam, NL was created to bring food production into urban areas to increase the resilience of food supply chains. The Floating Farm and has worked to implement a more circular dairy farming model by reducing land use and using recycled feed.

In this study, the circularity performance of the Floating Farm (FF) dairy production process was quantified using an indicator-based circularity assessment method. Indicators were derived from the FF's self-proclaimed circular actions and calculated using derived water, nutrient, and energy balances. A typical baseline farm was identified and used to compare indicator performance for which data was available and a comparison was relevant. From the mass and energy balances and indicator calculations, gaps in circularity were identified. To help close the gaps, scenarios to improve the farm's circularity were identified and assessed for feasibility. Each scenario was added to the indicator calculations to quantify the impact on indicator performance.

The results revealed several gaps in circularity, particularly concerning water and waste management. Once through cooling is currently used in the milk processing step leading to a very high water usage and wastewater production. In waste management, the entire liquid fraction of manure ends up in the sewer leading to significant nutrient and water losses. Generally, the farming model involves a trade-off that results in a loss of self-sufficiency, particularly regarding feed, water use, and electricity consumption. This is because no feed crops are grown, and there is no space for large-scale rainwater collection or solar energy production.

The scenario investigation revealed that switching the water source of once-through cooling water from the tap to river water is feasible, greatly impacts indicator calculations, and should be the priority for the farm to improve. The other three scenarios had several pros and cons but may be better suited for future versions of the farm due to the farm's current scale and lack of operational expertise in water treatment.

Despite the farm's efforts and enthusiasm, the indicator performance for most of the farm's circular actions have room for improvement. The farm has put effort into creating a circular economy but still must make significant strides to meet its goals. On top of the scenario recommendations, it was recommended that the farm install more measurement devices to increase the accuracy of future analyses and have a clearer view of process flows to more accurately identify losses.

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Nomenclature

Abbreviations

Abbreviation	Definition
AD	Anaerobic Digestion
Ag	Agriculture
BAT	Best Available Techniques Document
BOD	Biochemical Oxygen Demand
CE	Circular Economy
COD	Chemical Oxygen Demand
CP	Crude Protein
DEA	Data Envelopment Analysis
DO	Dissolved Oxygen
DW	Dry Weight
ECM	Energy Corrected Milk Yield
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FF	Floating Farm
FPCM	Fat Protein Corrected Milk Yield
GHG	Greenhouse Gas
IBC	Intermediate Bulk Container
LCA	Life Cycle Analysis
MRIJ	Meuse-Rhine-Issel
N	Nitrogen
NF	Nanofiltration
NL	Netherlands
OM	Organic Matter
OTC	Once-Through Cooling
P	Phosphorus
PV	Pressure Vessel
RI	Ryznar Index
RO	Reverse Osmosis
SDC	Dutch Sustainable Dairy Chain
SI	Saturation Index
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
WM	Water Mining
WP8	Water Mining Work Package 8

1

Introduction

As the earth has seen a global population increase and widespread industrialization in the last century, the traditional linear economy (make-take-dispose) has become increasingly unsustainable [1]. These practices of production and consumption have contributed heavily to climate pressures such as climate change, resource scarcity, loss of biodiversity, and greenhouse gas (GHG) emissions [2]. To decrease stress on natural resources and reduce waste, recent initiatives focus on implementing a more circular production model coined circular economy (CE). The definition of circular economy is ever-evolving and difficult to define due to its complexity in nature and interdisciplinarity [3]. Lei, Li, Yang, *et al.* [4] describes the circular economy as a systematic approach to disconnect economic growth from environmental burden by creating regenerative systems that rely on renewable sources. A circular economy uses the principles of reduce, reuse, and recycle to increase resource efficiency and in turn benefit our society, economy, and environment. In the Netherlands (NL) there is ambition to establish a CE by 2050. To evolve towards a circular economy, the Ministry of Agriculture, Nature, and Food Quality has developed a vision to transform the current supply chain into a system with minimal losses. A large problem is that the traditional linear system within the Dutch agriculture sector is highly successful at the cost of sustainability, making circular models difficult to implement [2].

The Netherlands has set lofty goals concerning emission reduction targets. The national climate agreement (Klimaatakkoord) introduces measures with the aim of reducing CO_2 by 55 percent by 2030 relative to 1990. In 2021 emissions had only decreased by 17 percent meaning there are significant reductions to be made in this decade. Current policy agendas focus primarily on quickly reducing Ammonia (NH_3) emissions while considering economic impacts [5]. Primary efforts to achieve this include rejecting old nitrogen policy which resulted in a large nitrogen surplus, and granting building permits which are conditional on achieving ammonia emission reduction.

The agriculture (Ag) sector is in a particularly difficult position because it contributes largely to GHG production, destruction of biodiversity, and high land use, and at the same time is largely vulnerable to climate change. Extreme weather events exacerbated by climate change can cause crop failure and loss of arable land leading to both economic and societal consequences. This is increasingly concerning due to the ever-growing demand for food worldwide because of population increase. The Ag sector needs to balance increases in production and climate change in order to continue providing for society's needs. The low-lying geography of the Netherlands makes climate adaptation in the agriculture sector paramount in ensuring food security in the future.

To adapt to the changing climate and ensure food security for the future, The Floating Farm (FF) aims to bring food production into cities to make food supply chains more resilient to natural disasters. The idea came about after flooding during Hurricane Sandy in New York led the city to begin running out of fresh food in a matter of days. This was primarily due to the long supply chains from producers to consumers which rely on truck transport [6]. Since most cities are located near water and as sea levels rise there will be less land to farm, floating farms present as an interesting solution. A floating farm is simply a farm built on water to increase resiliency in cities by reducing land use for agriculture and reducing food transport. The first floating farm was built in the Port of Rotterdam in 2019. This farm operates primarily as a dairy farm with approximately 30 cows. They sell cheese, milk, butter, and yogurt to consumers in Rotterdam. As well as aiming to increase the resilience of the agricultural supply chain, the Floating Farm has implemented circularity in the design of their farm. The farm operates with the aim of TransFARMation which works toward farming that is climate-proof, circular, sustainable, creates healthy food, is educational, and subsidy-free. The FF has partnered with the Water Mining (WM) project which aims to tackle issues with global water supply by exploring alternative water sources. The FF is a WM case study and several projects such as stakeholder analyses and development of technical improvement scenarios have been accomplished during their partnership. This thesis is a part of Water Mining's deliverables to the FF.

The primary objective of this thesis project is to quantify the Floating Farm's circularity performance by performing a circularity assessment. Additionally, four sub-objectives were derived. The first sub-objective is to compare calculated indicators with a typical baseline farm. The second sub-objective involves modeling different mass and energy flows to understand different processing step contributions to circularity. The third sub-objective is to identify potential aspects of improvement and give recommendations. The final sub-objective is to re-evaluate the circularity considering such improvements. These objectives help to derive the research question and sub-questions below.

The main research question:

What is the circularity performance of the Floating Farm dairy production process?

Sub questions:

1. *How does the circularity performance of the FF dairy production compare with a conventional dairy process?*
2. *How do different process steps contribute to the overall circularity of the dairy production process?*
3. *How can the circularity of the FF's dairy production process be improved?*
4. *How will suggested improvements impact the circularity of the dairy production process?*

2

Theoretical Background

2.1. Sustainability vs Circular Economy

The terms sustainability and circularity/ circular economy are often used in parallel and mentioned in the same context in both engineering fields and policy discussions. For the purpose of this thesis, it is important to differentiate the terms and clarify their relationship. It is also relevant to clarify the reasoning for the indicators chosen and their relationship to both circularity and sustainability. By increasing understanding of the subject, the methodology can be better explained and understood.

2.1.1. Sustainability

As one of the biggest buzzwords and topics of conversation across disciplines in the last few decades, sustainability has been thoroughly studied and defined. However, a simple definition of sustainability is difficult to acquire. Johnston, Everard, Santillo, *et al.* [7] points out that a simple dictionary definition implying something 'is able to be sustained' does not encompass the temporal component of sustainability and the intergenerational aspect that is often implied in sustainability initiatives and policies. This article also recognizes the need for a more universal definition of sustainability because it varies by field and can make it difficult to implement from a policy perspective [7]. In the review by Geissdoerfer, Savaget, Bocken, *et al.* [8] many definitions of sustainability are considered. The definition settled on is ”the balanced and systemic integration of intra and inter-generational economic, social, and environmental performance”. This definition considers the temporal importance of sustainability as well as the 'triple bottom line' of sustainability: people, planet, and profit.

The term sustainability is often tied to sustainable development initiatives likely because of the history and context surrounding the words. When the word entered mainstream political conversations in the 1980s, environmentalists wanted to show how environmental issues could be linked to development questions. A well-known report known as Our Common Future or the Brundtland Report offered the modern definition of sustainable development. “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [9]. This report and connection to development inspired academic and policy debate among many disciplines which made the terms the buzzwords they are today.

2.1.2. Circular Economy

Like sustainability, there have been several definitions of circular economy. The concept was first introduced in the late 1970s. Many consider the introduction of the topic to be in the 1989 book Economics of Natural Resources and Environment by Pearce and Turner [10]. This book describes how natural resources influence the economy in terms of production inputs and waste sinks [8]. The most commonly used definition is from the Ellen MacArthur Foundation describing the CE as “an industrial economy that is restorative or regenerative by intention and design” [8]. An important concept that is not implicitly stated in this definition is the principle of closing loops. Corona, Shen, Reike, *et al.* [11] describes CE as “a sustainable economic system where economic growth is decoupled from resources use, through the reduction and re-circulation of natural resources.” This definition is more explicit and will be used in this report.

In recent years the concept of circular economy has attracted attention from policy makers and scholars as a means of achieving sustainable development. In Europe, several circular economy packages and policy targets focusing on circular economy have been enacted. The main strategy behind implementation involves players in the industrial sector. Key principles behind strategies employed include sustainable design, energy, and material efficiency, waste reduction (reduce, reuse, recycle), business model innovation, and industrial symbiosis [11].

2.1.3. Comparative Analysis

Considering that circular economy is seen as a means to achieve many sustainability initiatives, there is an obvious relationship between these two concepts, but they are not void of differences. In Geissdoerfer, Savaget, Bocken, *et al.* [8] both similarities and differences are identified based off of an extensive literature search. Table 2.1 lists the similarities identified.

Table 2.1: Similarities between Sustainability and the Circular Economy from Geissdoerfer, Savaget, Bocken, *et al.* [8]

Similarities
Intra and intergenerational commitments
More agency for the different pathways of development
Global models
Integrating non-economic aspects into development
System design and innovation as a primary principle
Interdisciplinary research field
Potential cost, risk, diversification, value co-creation opportunities
Cooperation of different stakeholders necessary
Regulation and incentives as core implementation tools
The primary role of private business, because of resources and capabilities
Business model innovation as a key for industry changes
Technological solutions are important but hard to implement

These similarities are important to highlight and show how many general ideas behind the concepts are the same. The concepts share a scope and face similar challenges, but when looking into more specific attributes such as goals and responsibility many differences become apparent.

In Geissdoerfer, Savaget, Bocken, *et al.* [8] many differences are identified. These include origins, goals, motivations, system priorities, institutions, beneficiaries, and perceptions of responsibility. For the purpose of this thesis the most important differences include goals, motivation, beneficiary, and agency. For a full table of differences see Appendix A.

The goal of the circular economy seen most in literature is closing loops and eliminating leakages in a system. The goals of sustainability are more open-ended and the goal shifts depending on discipline. In terms of the primary motivation behind each concept, CE is motivated by the idea that resources can be better used and that a circular economy will help to reduce emissions and waste. Sustainability is motivated by negative environmental trajectory and motives are often diverse depending on the context.

The breadth of sustainability can also be seen in the beneficiaries which includes the economy, environment, and society at large. For CE the primary beneficiary is economic actors who implement the system. CE may also benefit the environment and society at large, but it is unlikely there will be much implementation without benefiting the economy. This is also seen in the underlying motivations. CE prioritizes economic systems that benefit the environment and indirectly benefit society. Whereas, in theory, sustainability aims to address all three dimensions equally. Finally, in terms of agency, sustainability initiatives are often dispersed amongst many actors while CE clearly emphasizes the roles of governments and corporations [8].

For this project specifically, it is important to understand the relationship between the two ideas to determine how they will interact in the circularity analysis. Also in Geissdoerfer, Savaget, Bocken, *et al.* [8] different relationship types based on literature findings were derived. The three main relationships include conditional, beneficial, and trade-off relationships. Depending on the context all three relationships can be relevant. For conditional relationships, CE systems are seen as a condition or element of sustainable systems/ sustainable development.Geissdoerfer, Savaget, Bocken, *et al.* [8] found that several authors agree on this to different degrees. Some describe CE as an important element, others consider it necessary for a future that sustains economic output, and several think it is necessary, but not sufficient as the only condition to creating a more sustainable society. The beneficial relationship means CE systems are beneficial in creating sustainability, but the authors who offer this relationship do not mention conditionality. Many papers in this category see CE as one of many solutions encouraging sustainability. The final relationship identified by Geissdoerfer, Savaget, Bocken, *et al.* [8] is the trade-off relationship. This considers that CE systems have both costs and benefits for sustainability which can lead to adverse outcomes. Some authors also consider that CE fosters some aspects of sustainability, but lacks in others.

2.1.4. In the Context of the FF

Circularity and sustainability are both important for future policies and initiatives and have distinct similarities and differences. Circularity is an important element of sustainability in many contexts, but not every circularity initiative is sustainable, and just because something is seen as sustainable does not mean it's circular. An example of this dilemma in the context of the FF is its feed model. Traditional dairy farms either grow or import their feed crop which is often neither sustainable nor circular due to large emissions, water use, use of pesticides, and large land use. In fact, 69 percent of agricultural land is used for pasture crops leaving less and less land to grow food for human consumption [12]. In this way, the FF's use of recycled feed is innovative and seen as a way into a more sustainable future. There are questions, however, as to whether the FF feed model is circular. A large part of a circular economy is self-sufficiency and with the current model, the FF depends on many sources of food waste. This is not currently a problem because food waste is in abundance, but if there was no food waste there would be no FF. It is also worth pointing out that the current feed model is completely reliant on a linear system. The current model of food production across the globe functions on extracting finite resources, is wasteful, creates pollution, and harms natural systems. Many initiatives including the FF are aiming to transform the food system and create a circular economy. This would in turn create a more circular and sustainable industry, but the FF would likely need to adapt. At a pilot scale, the current feed model of the FF is a nice way to reduce feed waste and land use from growing feed crops. However, there is a trade-off between self-sufficiency, and the current model may not be sustainable in the future if a true circular economy is adapted across sectors. These trade-offs will be further explored as indicators for the FF are calculated and conclusions are drawn about the FF's circularity.

2.2. Circular Transition in the Dutch Agriculture Sector

2.2.1. Circular Agriculture

Increasing efficiency and lowering emissions in food production specifically in the dairy industry is not a new idea. Almost two decades ago the Food and Agriculture Organization of the United Nations (FAO) determined that livestock is responsible for 37 percent of global methane emissions [13]. The dairy industry, however, has struggled to lower GHG emissions due to an ever-increasing global milk demand. From 2005 to 2015, the sector experienced an 18 percent increase in GHG emissions, as opposed to the estimated 38 percent increase that would have occurred had efforts not been taken to make the sector more sustainable and circular. [13]. In the Netherlands, current visions focus on shifting to circular agriculture principles to lower GHG emissions in a cost-effective manner. Circular agriculture focuses on closing resource cycles by increasing efficiency, recycling manure, lowering external inputs such as feed and pesticides, and improving systems as a whole [14].

The idea of circular agriculture was introduced by the Dutch Ministry of Agriculture, Nature, and Food Quality with the primary aim of maintaining its position as a global leader in agriculture by taking the initiative in the transition towards circular farming systems [15]. Vrolijk, Reijs, and Dijkshoorn-Dekker [15] points out that the definition of circular agriculture is rather vague on purpose to allow room for experimentation with many solutions. Circular agriculture takes more a small-wins approach to the transition from a linear economy to a circular economy as opposed to giant leaps. Some argue that giant leaps are what is necessary, but Vrolijk, Reijs, and Dijkshoorn-Dekker [15] points out that small wins allow time for policy to adjust to the transition and better protect the interests of farmers.

2.2.2. Structural Development of the Dairy Sector in the Netherlands

By understanding past developments in the Dutch agriculture sector, the future of a circular economy and its implementation can be better understood. The introduction of large-scale dairy farming began after World War II with the goal of restoring food provisions to the Dutch people after food shortages during the war. The Minister of Agriculture at the time, Mansholt, wanted to modernize and focus on large-scale farming. He led the integration of agriculture on a European scale leading to large growth in specialized dairy farming and intensive livestock farming. From the late 1950s to early 1970s this policy model was also supported by mechanization and new farming technologies. The European system created was not circular due to imports of cheap cattle feed and an interruption if the manure-food cycle (manure stayed in the country of production, but products were exported) [16].

From the early 1970s to around 2015, European Union (EU) policies such as the Common Agricultural Policy (to guarantee minimum prices) and technologies such as selective breeding and concentrated feeds, led to rampant increases in milk production. In the mid 80s, scientists began to notice problems related to resource depletion such as mad cow disease and acid rain from nutrient excesses. From this regulations and milk quotas were applied, but Dutch politicians prioritized the economic gains that industrialized farming provided. In 2015 the European milk quotas ended, and farmers began to ramp up production leading to detrimental effects on the environment such as nutrient regulations being exceeded. The government came up with new laws much to the dismay of the agricultural lobby. The concept of circular agriculture was introduced in 2018 and Dutch dairy farming is now at the threshold of returning to a circular economy. Compared to the last large transformation period (post-war) societal implications and consequences for farmers are more complex making implementation difficult. At its current state concrete measures have not been implemented on a large scale [16].

2.2.3. Current Initiatives

With government pressure, public perception. and economic drivers many large agrifood companies are eager to be a part of the transition to a circular economy. The problem is with most sustainability initiatives action must take place at a farm level. This is difficult for companies because most do not have direct relationships with farmers and cannot influence production. Large companies also often lack an understanding of farm management. Companies must also keep in mind existing market conditions and understand that food prices must remain competitive in the global market [15].

A current initiative developed by the Dutch agribusiness sector is the Dutch Sustainable Dairy Chain (SDC). Established by the Dutch Dairy Association and the Dutch Federation of Agriculture and Horticulture, the SDC aims to address concerns about sustainability and societal pressures within the sector. The SDC sets sustainability targets for members of the association and encourages the creation of future sustainability programs by its members [15]. A large part of SDC is also to help farmers identify best practices to achieve sustainability goals and help them apply such practices.

On an individual farm level Huiding [17] conducted interviews and looked into the circularity initiatives of several different dairy farms in the Netherlands. The corporation Circulair Friesland works to connect and encourage organizations, the government, schools, and businesses to use circularity principles and help the region become more circular. Companies can join on three themes including circularity in purchasing, circularity in construction, and closing nutrient loops. They help businesses who want to be more circular get together and help each other to accomplish their circularity goals [17].

Also interviewed was Friesland Campina, a large multi-national dairy conglomerate based in the Netherlands. They work with 10,000 member farmers and a revenue of 14 billion euros annually. They have implemented several circular initiatives. The TKI Agrofood project works on resource recovery from wastewater, and the WISE project works to return process water from factories back to the farmer. They also reuse fertilizers, recycle packaging, and use residual heat from production. They also research sustainability initiatives and have a sustainability strategy. Other institutions interviewed include Wagenaar Dairy, Tetra Pak, and Dero Groep. They all had circular initiatives in a similar realm as Friesland Campina specifically investing in waste management. The conclusion taken from Huiding's paper is that steps have been taken towards a circular economy within companies, but many production chains are still linear. Many companies mentioned the role of the government in creating a circular economy. Policy that supports circular innovation is considered essential in the next step of creating a circular economy [17].

2.2.4. New Business Models

To create a successful circular food system in the future Vrolijk, Reijs, and Dijkshoorn-Dekker [15] proposes an approach in which stakeholders play a role, farmers seek new business models with the support of research organizations, and governments help to facilitate the transition. Current business models focus on product pricing and quality requirements. For a more circular model, the value must be prioritized alongside circular and nature-inclusive agriculture. This transition is complex and cannot be accomplished by farmers alone. A collaboration amongst stakeholders across the supply chain, government, and consumers is necessary. A large challenge for implementation is demonstrating the value of nature-inclusive agriculture and finding a way to monetize such value. Another problem is due to the lack of unified vision on circular agriculture (also demonstrated in [17]). Many initiatives focus only on one aspect, but in reality, farmers encounter a system where trade-offs and synergies must be balanced around different objectives.

In the Netherlands, several studies have been conducted experimenting with different circular food systems and their business models. The examples show systems where money is generated and value is created for and with nature. These studies show that an optimal business model is different for every company because of different structures within each company, but successful farms use multiple business models in combination. There have been successful examples, but now the problem lies in figuring out how this can be up-scaled. Questions such as facilitation, who is paying, revenue distribution, and incentives are very relevant. For these relevant questions see table 2.2 below.

Table 2.2: Future questions for implementation of CE business models and the solutions offered by Huiding [17].

Relevant Questions	**Possible Solution**
How can successful examples of innovators and niche markets be scaled up to mainstream?	• Facilitation by major food companies • Making it compulsory by law
Who should bear the costs of the transition towards sustainability?	• The market • Citizens • Consumers
Should there be a shift to true pricing?	• Yes, to reflect all hidden costs of externalities that are not currently reflected in market prices • No, due to limited willingness to pay for sustainable products
How should revenues be distributed among stakeholders?	• Fair compensation for farmers for the extra costs and effort to produce sustainably • Monitoring prices in the food chain and distribution of profits
What are the challenges in implementing true pricing?	• Methodological challenges (choice of themes/factors, definition of indicators, quantification, comparisons between different dimensions, standardization, robustness, support) • Lack of sufficient empirical applications and evaluation
What tangible incentives and policies could support the desired transition?	• Financial policy measures such as subsidies to farmers or internalizing societal costs in market prices by taxing environmental impacts • Other policy options
How can consumers be informed about the societal costs of agri-food systems?	• Offering insight into hidden costs through true pricing • Information about “true prices” or “true costs”
How might consumers respond to policy measures affecting product prices?	• Consumers may respond to the impact of policy measures on product prices • Consumers may avoid products with negative environmental impacts and high societal costs if informed about true prices

The status and relevance of the circular transition are very relevant to the topic of the FF as they are very much a part of the transition. By understanding current ideas and initiatives surrounding the topic, it is easier to see where the FF fits and provides context. The Netherlands being at the forefront of the transition means stakeholders are more aware of the topic and will be more willing to collaborate. The FF is innovative in the field and presents an interesting educational opportunity for both farmers and consumers. The FF also serves as a living lab in the sense that companies and researchers can use the farm as a test site for circular innovations. The business model of the FF may also be an interesting case study for circular business models and their implementation, but this is not within the scope of this thesis.

2.3. Circularity Assessments in Literature

2.3.1. LCA approaches

In order to quantify circularity and emissions in a typical dairy farm, many studies have been completed using various modeling and life cycle assessment (LCA) approaches. In Wang, Ang, and Oude Lansink [14] they attempt to discover the extent to which optimizing land use (crop or grassland) can impact GHG emissions. They used a sample of Dutch dairy farms from 2010 to 2019, where farms implemented circularity by reusing crops as feedstock and reusing manure for crops on the farm. They created a complex network model, specifically a Data Envelopment Analysis model (DEA), to yield inefficiency scores for different scenarios of land use. In their study crop and livestock outputs were modeled separately. Examples of inputs for crop production include upcycled manure used as fertilizer for crops, total cropland, unsold crop residuals, etc. Animal units, purchased feed, animal health costs, total grassland, and surplus manure are examples of livestock production inputs. Wang, Ang, and Oude Lansink [14] offered a network structure (Figure 2.1) which is useful for understanding inputs and outputs for a typical farm system (a baseline farm). They concluded that there is limited potential to reduce GHG emissions through land optimization because many Dutch farms are already operating close to peak efficiency. The results suggest the largest reduction of GHG emissions can be obtained by sacrificing production or herd size.

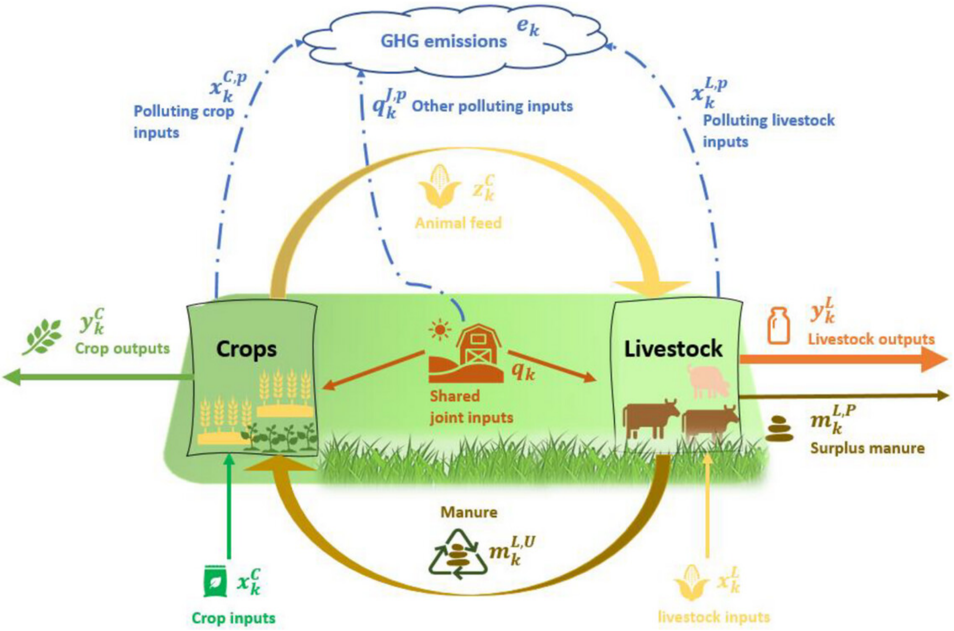

Figure 2.1: Network structure [14]

Drews, Czycholl, and Krieter [18] researched how dairy performance parameters influence environmental impact by using an LCA and linear mixed models to assess dairy farms in Northern Germany. The primary objective was to identify the most relevant performance parameters and quantify their effect on the four environmental impact categories. These categories include global warming potential, freshwater eutrophication, terrestrial acidification, and agricultural land occupation. Drews, Czycholl, and Krieter [18] concluded the higher the milk yield per area of agricultural land the larger the improvement in environmental efficiency. Capper and Cady [19] had a similar result when they looked at environmental impacts between 2007 and 2017 in United States dairy farms.

They stated that the key performance indicators that improve milk output per kg of cattle weight were the key determinants of GHG emissions per kg of milk.

With an alternative angle, Puente-Rodríguez, Van Laar, and Veraart [20] investigates using different feed sources to increase circularity such as food waste and seaweed to replace imported feed. This was relevant in other studies such as Rebolledo-Leiva, Vásquez-Ibarra, Entrena-Barbero, *et al.* [21] which found that the feed crop farming stage of dairy farming was far less efficient (efficiency index of 0.694) compared to the milk farming stage with an index of 0.798. When looking a scores of specific farms those that were considered inefficient used much more fertilizer, pesticides, and diesel in the feed crop farming stage [21].

These findings from typical farms are informative as background and context because the FF operates with a different model which focuses on increasing circularity through innovative waste management and recycled feedstock rather than specifically optimizing feed for increased production. Since previous assessments have highlighted the need for high yields/efficiency as a primary indicator in reducing GHG emissions, it will be interesting to investigate how a circularity assessment considering FF circularity initiatives compares. Assessments such as Wang, Ang, and Oude Lansink [14] determined that Dutch dairy farms are operating close to as circular as their current structure and production model allow. Literature regarding feed crop circularity is also relevant to the FF and brings context to why using recycled crops is in theory increasing the circularity. Although LCAs will not be done in this thesis these studies highlight important parameters of circularity that can be assessed through the indicators derived.

2.3.2. Indicator Based Assessments

Circularity indicators have become more prominent as The European Commission has made CE a high priority as a part of the European Green Deal. To monitor performance, clear indicators are needed to assess how CE is impacting environmental goals. Many indicators already exist and include everything from resource flows to economic impacts [22]. Saidani, Yannou, Leroy, *et al.* [23] recognized the need for a set of reliable indicators and complied a taxonomy of indicators from previous literature. This article helped establish context and the need for organization and meaning behind chosen indicators, but these indicators have not been explained or used in practice and this article simply organizes them and does not assess how effective they are at measuring circularity.

Velasco-Muñoz, Mendoza, Aznar-Sánchez, *et al.* [24] is much more relevant in the context of FF. They list indicators focused on narrowing resource loops, closing resource loops, and regeneration within agriculture. This article also mentioned the strengths and weaknesses of each indicator. They highlight data availability limitations and complexity to calculate. Some only focus on one type of crop or agricultural practice and cannot be generalized within the context of the FF. The most useful indicators in this paper are resource flow indicators. Many were similar to indicators developed by Water Mining Work Package 8 (WP8), and it is useful to compare those developed by Water Mining with the indicators in Velasco-Muñoz, Mendoza, Aznar-Sánchez, *et al.* [24] which are given in a more agricultural context. The framework for an indicator-based assessment will be further explained within the methodology, but previous frameworks used serve as background for chosen indicators and help to validate indicators used by WM. Indicator-based assessments are less common to find which is likely due to the current lack of standard indicators as stated by Loon, Vonk, Hijbeek, *et al.* [22] and Saidani, Yannou, Leroy, *et al.* [23]. A generalized list may be interesting, but can only be taken so far as different parameters should be assessed depending on the sector and application.

2.4. The Water Mining Project and the Floating Farm

This thesis is a part of a larger collaboration between Water Mining and the FF. Water Mining aims to help the world meet global water demands and ensure access to clean water and sanitation by researching alternative water sources. They focus on utilizing wastewater and seawater as alternative sources specifically. The FF is a part of one of WM living lab initiatives and the wider project focuses on identifying stakeholder and citizen perspectives for a redesign of the farm.

3
Methods

3.1. Circularity Assessment Framework

The methodology for circularity assessment for the FF was adapted from a Water Mining Deliverable Work Package 8 (confidential). This deliverable focuses on circularity and sustainability evaluation and demo activities. Figure 3.1 explains the primary methodology steps from Water Mining WP8. The primary steps were adapted from Nika, Vasilaki, Renfrew, *et al.* [25] and include system development, indicator selection, circularity measurement, system testing, and final assessment.

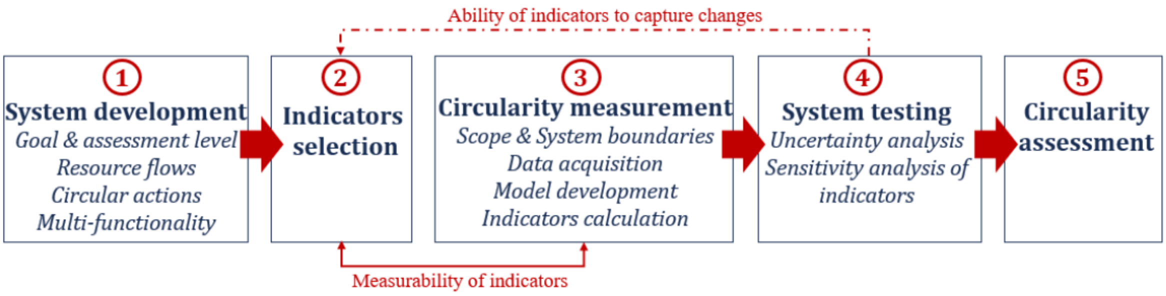

Figure 3.1: Framework from WP8 adapted from Nika, Vasilaki, Renfrew, *et al.* [25]

3.2. System Development

3.2.1. Goal and Assessment Level

The first step of the framework regards identifying a goal and an assessment level for analysis. The goal was derived from the research questions and should describe the targeted problems that will be addressed by the analysis. The assessment level describes the level of detail within the analysis and the focus. Examples of assessment levels include product level, organizational, process, industrial symbiosis, and national level.

3.2.2. Resource Flows

Before circularity was assessed, the process/resource flows were identified. These flows were identified by making process diagrams for water, energy, and nutrient flows and a whole farm diagram. The primary on-farm processes considered include milk production, milk processing, and waste management.

3.2.3. Circular Actions

Before indicators can be derived circular actions that the farm self-identified were compiled. A circular action is an action the FF is currently taking or claims to be taking to make its dairy farming model more circular than a typical farm. To choose circular actions, statements from the media and interviews with employees were used. The idea was to assess the farm based on what the FF claims make them circular with circularity indicators that come from those circular actions.

3.3. Indicator Selection

Water Mining WP8 contained an indicator selection process (adapted from Nika, Vasilaki, Renfrew, *et al.* [25]) that was modified to fit the assessment of the FF and the time constraints of this thesis. Figure 3.2 outlines the indicator selection framework from Nika, Vasilaki, Renfrew, *et al.* [25].

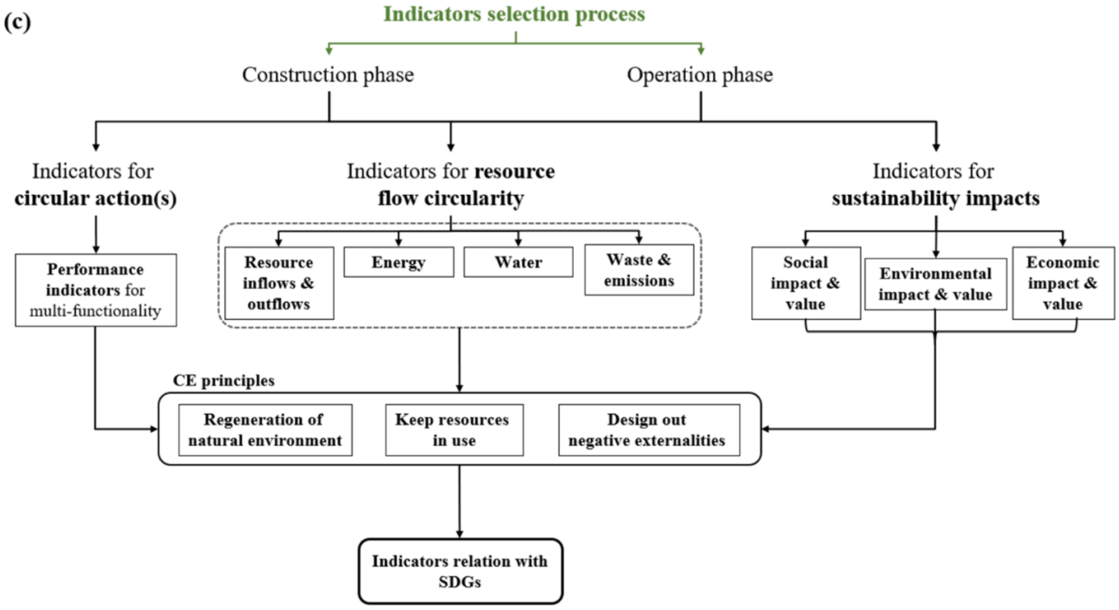

Figure 3.2: Indicator selection framework from Nika, Vasilaki, Renfrew, *et al.* [25]

Figure 3.2 was followed for indicators for circular actions and flow measurements, but for this assessment sustainability impacts were not considered due to time restraints and lack of data. To select indicators based on the circular actions identified, WP8 was used as a guide by looking at previous case studies and the indicators chosen for similar actions that were also relevant to the FF. For the more specific actions, many indicators were derived from what felt important to measure based on the circular action. Questions such as “how can this be measured”, and “what data can be collected regarding this action” were vital in coming up with measurable outcomes. Indicators were also derived by and inspired by literature more specific to circularity indicators in agriculture. Velasco-Muñoz, Mendoza, Aznar-Sánchez, *et al.* [24] and Saidani, Yannou, Leroy, *et al.* [23] helped apply this framework to an agricultural setting.

Two different types of indicators were derived: indicators that assess the individual performance of the FF and analyze improvements from scenario implementation, and comparative indicators that directly compare the baseline farm and the FF. The indicators are considered and displayed separately because they serve different purposes in the analysis.

3.4. Circularity Measurement

3.4.1. Scope and System Boundaries

The scope and system boundaries were narrowed based on several factors such as data availability, ability to compare to the baseline, and ability to answer the research question. To assess the circularity of the farm a base model including a nutrient, energy, and water balance was created in Excel. The scope focuses on inputs and losses on the farm only and disregards both the office and the vertical farm systems. For example, ammonium losses after manure product is used in fields and water to grow crops used as feed were considered out of scope. The office was considered out of scope because its usage tells nothing about the circularity of the farm processes, and comparisons with other farms or literature only focus on farm performance. The vertical farm is also disregarded because it is not connected to the production of milk in any way and also throws off the comparison to a typical dairy. The vertical farm that existed when the majority of data was collected has also since been deconstructed and a completely new design is being built so any circularity claims of the old design would be useless.

3.4.2. Methods of Comparison

Baseline Farm

An important part of system development included choosing a baseline of comparison as a "typical" dairy farm. The farm Veelon, located in Noord Brabant, has approximately 230 cows and operates at a much larger scale than FF. The reason Veelon was chosen is due to comparable data already available from Namjesky's bachelor thesis. Namjesky sent the same survey to both FF and Veelon and compared their circularity on a more qualitative level. For the baseline, both Namjesky's thesis and the raw data collected were useful, and time did not have to be spent collecting data for the baseline. The data collected from Veelon was used to calculate comparative indicators that compared the FF to the baseline. There was no data available from the baseline for all indicators, and some comparisons were not realistic due to completely different farming models, but where it was realistic and data was available, the comparative indicators were calculated. Table 3.1 below indicates the important characteristics of the two farms.

In order to compare the two farms the data had to be normalized. In literature, many performance figures for dairies are reported in terms of Energy Corrected Milk Yield (ECM), or Fat Protein Corrected Milk Yield (FPCM) in the Netherlands. The fat and protein content was available for the FF to normalize by FPCM, but not for the baseline. Instead, the data was normalized by L/milk produced per day per cow. The energy and fat/protein corrections may slightly impact results, but using L milk/day is straightforward and often reported in other studies. The number of cows was also taken into account for the baseline comparisons to obtain the same scale. For most indicators, the data was divided by the total milk produced per day assuming all cows produce the same amount.

Table 3.1: Defining Characteristics of the FF and Baseline to demonstrate the difference in scale

FF Critical Characteristics			**Baseline Critical Characteristics**	
Parameter	***Amount***	***Unit***	***Amount***	***Unit***
Milk produced	24	L milk/cow/day	26.96	L milk/cow/day
Number of cows	30	cows	230	cows
Total L per day	720	L milk/day	6200.8	L milk/day
Grazing Area	0.18	ha	85	ha

Comparison with Literature

For the nutrient, water, and energy balances, some comparisons were made with literature. The same normalization was used for these balances as for the indicators as it is most common to see figures reported by L milk, kg milk, or ECM/FPCM. With the method of normalization chosen it is easy to compare with literature. For sources reported as kg milk instead of L, the data must be multiplied by the density of milk (1.03 kg/L). Best Available Techniques (BAT) Reference Document for the Food, Drink, and Milk Industries was used as a comparison and guide for water use and energy use in processing. The metrics in this document were presented with units per tonne of milk making the normalization by L milk for the FF easy to compare with.

Internal Performance

For all calculations, the FF itself was a reference and its performance individually was being measured against the circularity claims the farm has made. Measuring its performance also allowed for the identification of circularity gaps and improvement scenarios. For this assessment, normalization was not necessary but was used to keep everything consistent throughout the report and with literature.

3.4.3. Data Acquisition

In order to quantify the circularity initiatives of the FF, process data primarily regarding water, energy, and nutrient flows was gathered and used to calculate mass balances and circularity indicators. Methods of collection included two surveys, farm visit interviews, and literature searches.

Surveys

In order to accomplish this thesis one survey was made, and a survey from a bachelor thesis by Namjesky [26] (see Appendix C.1 table C.1) was used. Data for the baseline farm was the primary information gained from this survey. Much of what was collected regarding the FF was outdated or inaccurate. A new survey was made to collect data regarding process flows in order to complete mass balances and calculate indicators (see Appendix C.1 table C.2). Many of the questions asked in this survey were not directly known and had to be assumed or based on literature. Key information such as feed composition, energy bills, and water use from Evides was known. The surveys were used as questions asked in on-farm interviews with the operational manager, head grower, food specialist, and farmer. Specific questions also came up often while calculating indicators and as the thesis progressed. These questions were answered by going and working at the farm and being in the same room as the operational manager of the farm.

Data from Literature

The remaining data was assumed from literature. Important information regarding nutrients in each feed ingredient, distribution of nutrients after separation, and ammonium losses assumed based on previous studies. Much of the data collected from literature is standard throughout the dairy industry. Examples include the weight of a Meuse-Rhine-Issel (MRIJ) cow, yield per hectare of certain crops, percent water in milk etc. See appendix C.1 table C.2 for details on data collected including source. Methods of collection involved a literature search on Google Scholar and Google using keywords depending on specific needs. Sources vary from scientific papers, to informational brochures for farmers, to farming blogs. The use of diverse sources is due to challenges in finding useful data. Most sources are from the Netherlands, but sources from the United Kingdom, Germany, and the United States were used when necessary. All sources collected were in English. It is likely the varied sources bring significant error into the model, but with no alternative, still offer useful insight in estimating the FF's process flows and circularity.

3.4.4. Model Development

To assess the circularity of the farm a base model including a nutrient, energy, and water balance was created in Excel based on identified resource flows. To visualize the identified resource flows, Sankey diagrams were made for each balance. Each was normalized by L milk/day. To best understand data origins and uncertainty the flows were color-coded. If the flow is in green it is known with certainty by the farm by measurement or from a third party such as water usage from Evides. If the flow is in yellow the data is a mix of known information and data from literature. For example for the nutrient balances, the feed type, amount, and dry weight are known from the farm and used to determine the amount of nutrients based on the amount of feed, but the specific concentration of each nutrient in each feed constituent is from literature. If in orange the flow is a mix of estimated data from the farm and from literature, or based on a flow that is estimated. For example, most of the flows in the water balance are orange because water use for specific processes is not measured by the farm. The nutrient balances are also mostly orange because the nutrients from the feed input already contain uncertainty and the uncertainty is only compounded by additional assumptions from literature for each process. If the flow is red, it was assumed to close the balance. Most red flows, however, were only assumed if it was logical to do so and the processes were investigated as much as the limited data would allow.

Nutrient Balance

To conduct the nutrient balance a standard feed mix was first selected. Initial data obtained from the farm had reported mixes from December 2023 to April 2024. They are relatively standard and vary depending on what has been collected from the city waste (orange peels, green beans, etc.). The primary feed of Bierbostel, Grass from the stadium, and DDGS Proticorn did not vary extensively. The chosen configuration for the balance disregarded the small addition of 'treats' from the city and only accounted for the primary consistent ingredients. After a feed mix was chosen the nitrogen (N) and phosphorus (P) content of the mix was determined from values in literature and the dry weight (DW) of the feed. For P values were reported in mg P/kg DW feed or % dry weight[27]–[29]. For N, the values in literature were reported either as %N of the dry weight, mg N/kg DW, or as crude protein (CP) (%) [27], [29], [30]. If reported as CP a conversion of 16% of CP is N from literature was used [31].

After determining the nutrients that were input into the milk production system, data regarding the amount of N and P in urine in manure from literature was used along with the weight of manure produced to calculate how much N and P (kg/year) was excreted into the waste stream [32], [33]. The amount of nutrients in the wet fraction were known from an analysis performed by the FF, and the nutrients in the solid fraction were estimated based on N and P in manure from literature. Once the amount of nutrients in the slurry was determined (sum of nutrients in manure and urine) the distribution after mechanical separation into liquid and solid fraction was estimated based on a nutrient balance from Aguirre-Villegas, Besson, and Larson [34]. In Aguirre-Villegas, Besson, and Larson [34] a nutrient balance was performed for different methods of ammonium reduction. The method used for separation (screw press) was the same as FF so a similar distribution can be assumed. To keep the model process level, the amount of cheese made per week, the ratio of cheese to whey, and the % N and P in whey were used to determine losses from whey being disposed in the sewer [35]–[37]. What was not considered whey or cheese was assumed to be in the other products (milk, butter, buttermilk, and yogurt). Table 3.2 below summarizes the parameters used for the nutrient balance and indicates if the data was derived from literature or collected from the FF.

Once the balance was complete a Sankey diagram was made to better visualize flows, and several nutrient efficiency indicators were calculated to better understand circularity challenges for nutrient efficiency and losses. The Sankey diagram was normalized by L milk produced per day and the diagram reports flows with the unit g N/L milk. Because of papers such as Aguirre-Villegas, Besson, and Larson [34], there are studies to compare this balance to and assess the validity of the methods. For this reason and for the sake of time, a full balance for the baseline farm was not performed. For full raw data and sources used for all mass balances see table C.2 in appendix C.1. Equations 3.1 and 3.2 were used to calculate the nutrient balances and describe the inputs and outputs of the system.

$$N_{\text{feed}} \times \text{Feed}_{\text{input}} = N_{\text{solid}} + N_{\text{liquid}} + N_{\text{whey}} + N_{\text{products}} + NH_{3\text{ losses}} \tag{3.1}$$

where:

- N_{feed} is the concentration of nitrogen in the feed.
- $Feed_{input}$ is the total amount of feed input into the system.
- N_{solid} represents the amount of nitrogen in the solid fraction of manure.
- N_{liquid} denotes the amount of nitrogen in the liquid fraction of manure.
- N_{whey} refers to the amount of nitrogen in the whey.
- $N_{products}$ stands for the amount of nitrogen in milk products.
- $N_{H_3\,losses}$ accounts for the amount of ammonia lost.

$$P_{\text{feed}} \times \text{Feed}_{\text{input}} = P_{\text{solid}} + P_{\text{liquid}} + P_{\text{whey}} + P_{\text{products}} \tag{3.2}$$

where:

- P_{feed} is the concentration of phosphorus in the feed.
- $Feed_{input}$ is the total amount of feed input into the system.
- P_{solid} represents the amount of phosphorus in the solid fraction of manure.
- P_{liquid} denotes the amount of phosphorus in the liquid fraction of manure.
- P_{whey} refers to the amount of phosphorus in the whey.
- $P_{products}$ stands for the amount of phosphorus in milk products.

Table 3.2: Summary of Parameters Used from FF and Literature - Nutrient Balance

Parameters from FF	
Parameter	*Unit*
Nutrient analysis of liquid fraction	g/kg DW
Manure	kg/day
Feed Composition	kg/day
DS of feed	%
Parameters from Literature	
Parameter	*Unit*
Amount of N&P in feed ingredients	kg/day, or g/kg DW
% N in a cow	%
% P in a cow	%
Crude Protein in milk	%
Nitrogen in manure	%
Phosphorus in manure	%
Distribution of N&P after separation	%
NH_3 lost after storage	%
Whey to cheese percentage	%

Electricity Use

Like the nutrient balance, energy usage was calculated using a mix of known data, standards, and values from literature. It is considered a calculation of energy use, not an energy balance because of the narrowed scope. Only electric energy is considered because the farm does not have a gas connection. Any off-farm usage such as energy to produce crops is considered out of scope. The amount of energy used was known by energy bills from the farm in 2023 and solar production was determined by data collected by the farm and given through the Montreal Solutions data platform. In the bills obtained, it was discovered that there are two different electrical hookups on the farm. After further investigation, it was determined that one services the farm and the other services the office and store. Any solar energy produced only goes to the farm. This was useful to know when figuring out the distribution of usage throughout the farm. The total input used was a sum of the average of solar production and energy for the farm only (energy use by the office and store were not considered).

For dairy production, the Lely Astronaut robot milks the cows and is the main user of energy use in this step. The electrical rating of the robot was obtained from literature [38]. For waste management, energy is used for the manure collection robot and manure separation. Separation is done using a screw press separator. To determine the energy use from the screw press an electrical rating from a similar device in literature was used [39]. To feed the cows the feed is first mixed using a Sieplo feed mixer. Energy ratings for the exact mixer could not be found so an estimation based on similar mixers in literature was used [40].

The vertical farm is also responsible for energy use for lighting and heating. The vertical farm is considered out of scope in this analysis, but the balance can not be complete without it. An estimation of its usage was determined based on the lights and heaters used to most accurately complete the balance. The data used was for the old version of the farm because the energy bills used were collected when it was still operational.

Energy used for milk processing (mostly heating and machinery) was determined by using the standard energy consumption for the production of milk in European dairies (kWh/kg raw material) from the Best Available Techniques Document [41]. This document gave a range and a number in this range was selected that would close the balance after determining the energy use of the other processes. it is important to note that it is unknown if the energy usage reported in the BAT is purely electrical. Heating could be from a gas boiler with different efficiencies. The range reported was used more as a verification of the number that closes the balance, but it is still important to understand that the value reported may not be completely comparable. The energy was then visualized in a Sankey diagram normalized by L milk/day with final units being Wh/L milk. Table 3.3 below summarizes the parameters used for the electric use and indicates if the data was derived from literature or collected from the FF.

To derive the energy use balance equation 3.3 described below was utilized.

$$\begin{aligned} Energy_{in} - Energy_{vertical\_farm\&office} = {} & Energy_{milk\_production} \\ & + Energy_{waste\_management} + Energy_{milk\_processing} + Energy_{vertical\_farm} \end{aligned} \tag{3.3}$$

where:

- $Energy_{in}$ is the total energy input, which includes energy sourced from the network and solar energy.
- $Energy_{vertical\_farm\&office}$ is the energy needed for the vertical farm and office subtracted from the input to exclude from the analysis.
- $Energy_{milk\_production}$ represents the energy used for milk production processes, including operations such as Lely robot milking and feed mixing.
- $Energy_{waste\_management}$ denotes the energy required for waste management activities, including waste collection and separation processes.
- $Energy_{milk\_processing}$ refers to the energy consumed during milk processing operations.
- $Energy_{vertical\_farm}$ stands for the energy used for activities related to vertical farming, such as lighting, climate control, and irrigation.

Table 3.3: Summary of Parameters Used from FF and Literature - Energy Use

Parameters from FF	
Parameter	*Unit*
Energy summary for the year (total energy used in 2023)	kWh/month
Solar energy from weather station	kWh/month
Parameters from Literature	
Parameter	*Unit*
Power for Separator	Watt
Power for feed mixer	Watt
Power for Lely Astronaut (milking robot)	Watt
Power for Lely Discovery (manure robot)	Watt
Average usage from European dairies	MWh/ tonne milk

Water Balance

For the inputs of the water balance, water from the farm's rainwater collection system and Evides were considered. To determine the capacity of the water collection system the roof area and average precipitation and evaporation in NL was used [42], [43]. The consumption from Evides was obtained via access to their platform which reported usage in L/day. The identified users of water include milk production, the office, milk processing, and the vertical farm. Water for the office and vertical farm was considered out of scope and was not considered within the balance. This is because indicators and comparisons account only for on-farm use. The water used for the vertical farm and office is also minimal (approximately 200 L/day) which was subtracted from the input from Evides at the start. For milk production, water is primarily needed for cow drinking water and cleaning water. The water in the waste slurry, milk, and what was retained in the cow was determined based on how much the Lely Astronaut uses, flow rates of pressure washing and estimated time for washing, standard percentage of water in milk, and percentage of water in a cow (assumed to close balance) [38], [44], [45].

For milk processing, the main use of water is for cleaning and cooling. To determine how much cleaning water was used, the size and number of machinery, the cleaning practices (number of rinses), and water for flushing the system were considered. There is also water used in the cheese-making process to rinse the cheese and the amount of water used for the FF was reported by the cheese maker.

There was a large amount of water that was unaccounted for in the balance and it was assumed to be used in cooling. Most of the cooling uses glycol and recirculates water which would not be the source of a very large discrepancy. With further investigation, it was discovered that a compressor in the system uses once-through cooling (OTC) with tap water to cool the compressor. The compressor must be running for the cooling system to operate meaning there is a tap on for many hours a day (unspecified how many exactly). After doing a small experiment to measure the flow rate from a tap near the compressor and obtaining a rate of approximately 12L/min, the compressor was assumed to be the source of the discrepancy, and the cooling water amount was assumed to close the water balance.

To solve the water balance equation 3.4 was used with the parameters described in table 3.4.

$$\text{Water In} = \text{Milk Production} + \text{Slurry} + \text{Cleaning Wastewater} + \text{Cooling Wastewater} + \text{Cheese Wash Wastewater} \tag{3.4}$$

Where:

- **Water In** is composed of:
  - *Rainwater*
  - *Water from Evides*
  - *Water in Feed*
- **Milk Production** is composed of:
  - *Water in Milk (Product)*
  - *Cow Retained in the Cow*
- **Slurry** is composed of:
  - *Solid Fraction (Product)*
  - *Liquid Fraction (Wastewater)*
  - *Robot Water (Wastewater)*
  - *Pressure Washing (Wastewater)*

The water balance was then visualized in a Sankey diagram normalized by L milk/day. The final unit was L water/ L milk.

Table 3.4: Summary of Parameters Used from FF and Literature - Water Balance

Parameters from FF	
Parameter	*Unit*
Rainwater collection area	m^2
Water for milking robot	L/day
Evides water usage	L/day
Pressure washing frequency	time washing/day
Cleaning water (processing)	L/day
Cooling water (processing)	L/day
Water for cheese production (washing cheese)	L/day
% water in manure after separation	%
Parameters from Literature	
Parameter	*Unit*
Rainfall per year	L/year
Evaporation per year	L/year
Water use in office	L/day
% Water in milk	%
Amount of urine per day	L/day
% Water in urine	%

3.4.5. Indicator Calculation

Because most indicators were derived from WP8, and are primarily simple efficiencies, percentages, and comparisons with the baseline, indicator calculation was a simple process mathematically. The difficulty in this step was acquiring and estimating the data used. Most process flows were quantified through the process model/ mass balances, but several side calculations and specific data were also needed.

Circular Action: Using Renewable Energy Indicators

Table 3.5 below shows the calculation procedure, formulas, and parameters used for this set of indicators. There was data available for the baseline's energy usage so both indicators were also calculated for the baseline farm to be used to compare. To obtain a more relevant comparison, the energy for processing was left out in the second calculation of both indicators for the FF. To account for the size difference of the farms the energy was normalized by L milk produced per day. The indicator circular process energy intensity required the differentiation between fossil and renewable energy. To consider this, statistics from the energy company ENGIE were used from the yearly report given to the FF. They report using approximately 60% fossil energy and 40% for their energy makeup. Knowing this the energy from the grid was multiplied by both 40 and 60 percent to obtain the values for fossil and renewable energy.

Table 3.5: Using Renewable Energy Indicators, Parameters, Units, and Formulas

Indicator	**Formula**		
Electrical energy self sufficiency	$\frac{\text{Internally derived energy used}}{\text{Total energy used}} \times 100$(3.5)		
Parameters Used to Calculate	*Amount FF*	*Amount Baseline*	*Unit*
Milk production per/cow/day used to normalize	24	26.9	L milk/cow/day
Average solar energy produced	5.11	277.78	kWh/day
Total energy demand (grid+solar)	54.69	430.56	kWh/day
Total energy demand (grid+solar) w/o processing	37.52	–	–
Average solar energy produced in a year (Normalized)	0.21	0.045	kWh/L milk
Total energy demand (grid+solar) (Normalized)	0.075	0.069	kWh/L milk
Total energy demand (grid+solar) w/o processing (Normalized)	0.052	–	–
Indicator	**Formula**		
Circular process energy intensity	$\frac{\text{Fossil energy}+\text{Renewable energy}-\text{Internally Derived energy}}{\text{Mass of product}+\text{Mass of recovered product}}$(3.6)		
Parameters Used to Calculate	*Amount FF*	*Amount Baseline*	*Unit*
Fossil energy	29.75	91.67	kWh/day
Renewable energy	19.83	61.11	kWh/day
Fossil energy w/o processing	22.51	–	kWh/day
Renewable energy w/o processing	15.01	–	kWh/day
Internally derived (solar energy)	5.11	9.26	kWh/day
Mass of product (raw milk)	743.76	6404.60	kg/d
Mass of recovered product (manure)	271.20	10,500.00	kg/d

To compare the differences in demand between the two farms directly, an energy demand minimization calculation was completed. For this calculation, the processing usage by FF was not considered to obtain a more realistic comparison. Because of the inherent differences between the farms, this comparison is considered separately from the indicators which focus more on individual performance. Table 3.6 displays the calculation procedure and parameters used.

Table 3.6: Comparison with Baseline: Circular Action, Using Renewable Energy

Circular action: Using Renewable Energy, Comparative Indicator		
Indicator	**Formula**	
Electrical energy demand minimization	$\frac{\text{Energy Demand}_{\text{Baseline}}-\text{Energy Demand}_{\text{FF}}}{\text{Energy Demand}_{\text{Baseline}}} \times 100$(3.7)	
Parameters Used to Calculate	*Amount FF)*	*Amount Baseline*
Total energy demand (grid+solar) w/o processing (Normalized)	0.05	0.07

Circular Action: Water and Nutrient Recovery Indicators

To calculate the indicators for ‘Water and Nutrient Recovery’ the calculated water and nutrient balances were used. In the current version of the farm, the liquid fraction of the slurry is all considered lost (water and nutrients). For the water recovery in products, the water in the cows is considered with the products because it does not leave the system. For the baseline farm, there was no detailed data for this set of indicators so only the FF was evaluated. Since these indicators are percentages and there is no external comparison, normalization was not needed for these indicators. For the procedure, parameters, and units necessary to calculate the indicators see table 3.7 below.

Table 3.7: Water and Nutrient Recovery Indicators, Parameters, Units and Formulas

Circular Action: Water and Nutrient Recovery		
Indicator	**Formula**	
N recovery rate	$\frac{\text{Amount of N recovered (In milk, cows \& manure)}}{\text{Total entering amount of N}} \times 100 (3.8)$	
Data Used to Calculate Indicator(FF)		
Parameter	*Amount*	*Unit*
N retained in cow	1.61	kg N/day
N in milk	4.41	kg N/day
N in solid fraction of manure	2.24	kg N/day
N input (in feed)	20.01	kg N/day
Indicator	**Formula**	
P recovery rate	$\frac{\text{Amount of P recovered (In cow, in milk, in manure)}}{\text{Total entering amount of P}} \times 100 (3.9)$	
Data Used to Calculate Indicator(FF)		
Parameter	*Amount*	*Unit*
P retained in cow	0.39	kg P/day
P in milk	0.34	kg P/day
P in solid fraction of manure	1.42	kg P/day
P input (in feed)	5.61	kg P/day
Indicator	**Formula**	
Water recovery in products	$\frac{\text{Amount of water recovered in products}}{\text{Total entering amount of water}} \times 100 (3.10)$	
Data Used to Calculate Indicator(FF)		
Parameter	*Amount*	*Unit*
Water in solid fraction of manure	325.44	L/day
Water retained in cow	969.25	L/day
Water in milk	626.40	L/day
Total water usage	19,030.65	L/day

Circular Action Indicators: Waste Minimization

To measure the impact of collection manure as a biofertilizer two indicators regarding the FF's waste were calculated. The nutrient and water balances were also used to obtain waste flows and mass of resource inputs. Data for the baseline was not available for these indicators, so only a self-evaluation of the FF is considered. Table 3.8 below shows the procedure and parameters used to calculate these indicators.

Table 3.8: Waste Minimization: Indicators, Parameters, Units and Formulas

Circular Action: Waste Minimization		
Indicator	**Formula**	
Waste index	$\frac{\text{Mass of waste}}{\text{Mass of resources used}} \times 100 (3.11)$	
Data Used to Calculate Indicator(FF)		
Parameter	*Amount*	*Unit*
Weight of the liquid fraction of manure	1265.60	kg/day
Waste water from milk processing	15,923.15	kg/day
Feed input	1142.00	kg/day
Water input	19,030.65	kg/day
Indicator	**Formula**	
Waste utilization index	$\frac{\text{Utilized waste}}{\text{Utilized waste+Total waste produced}} \times 100 (3.12)$	
Data Used to Calculate Indicator(FF)		
Parameter	*Amount*	*Unit*
Weight of the liquid fraction of manure	1265.60	kg/day
Weight of the solid fraction of manure	542.40	kg/day
Wastewater from milk processing	15,923.15	kg/day

Circular Action Indicators: Using a Non-Finite Source of Water

The indicator for “Using a Non-finite Water Source” was easy to calculate since the water balance was complete. The water self-sufficiency of the baseline is assumed to be 100% because all water used on the farm is extracted from a well on the property. See table 3.9 below for the procedure and parameters used to calculate this indicator.

Table 3.9: Using a Non-Finite Water Source: Indicators, Parameters, Units and Formulas

Circular Action: Using a Non-Finite Water Source		
Indicator	**Formula**	
% water self sufficiency	$\frac{\text{Internally derived water used}}{\text{Total water used}} \times 100 (3.13)$	
Data Used to Calculate Indicator(FF)		
Parameter	*Amount*	*Unit*
Rainwater	513.70	L/day
Total water used	19,030.65	L/day

Circular Action Indicators: Eliminate Transport to a Processing Facility

To calculate the indicator for ‘Eliminate Transport to a Processing Facility’, the CO_2 emissions for transport for both FF and the baseline were calculated and compared. The locations of the feed sources were known, but assumptions were made to calculate this indicator. The processing center for the baseline was not known, so the nearest Friesland Campina facility was assumed to be where processing takes place. Once locations were known, distances were assumed using Google Maps. Literature regarding CO_2 emissions for long haul trucks, urban trucks, and electric vehicles was used to determine g CO_2/kg-km. For the baseline, long haul trucks were assumed as the vehicle, whereas urban and electric vehicles were used for the FF depending on which was specified in the survey. From speaking with the FF most feed is delivered once a month besides the DDGS which is delivered every 2-3 months. This was utilized when calculating the CO_2 emissions for DDGS delivery. For the baseline, no delivery schedule was given so once a month was assumed. Data was normalized by L milk/cow produced per day.

See table 3.10 and 3.11 below for the parameters and procedure used for individual and comparative indicators.

Table 3.10: Eliminate Transport to a Processing Facility: Indicators, Parameters, Units and Formulas

Circular action: Eliminate Transport to a Processing Facility					
Indicator	**Formula**				
CO2 emissions from transport	$\sum(\text{Distance}_i \times \text{Feed}_i \times \text{Emissions}_i)$ (3.14)				
Data Used to Calculate Indicator(FF)			**Data Used to Calculate Indicator(Baseline)**		
Parameter	*Amount*	*Unit*	*Parameter*	*Amount*	*Unit*
Distance travelled to deliver biofertilizer	10	Km (1 way)	Distance travelled to milk processing	46.90	Km (1 way)
Distance travelled brewery (for BSG)	1.10	Km (1 way)	Distance travelled brewery (for BSG)	165	Km (1 way)
Distance travelled stadium (for grass)	9.10	Km (1 way)	Distance travelled for concentrate	30	Km (1 way)
Distance travelled for DDGS	27.90	Km (1 way)	Distance travelled for maize	20	Km (1 way)
Biofertilizer transported per month	8135.98	kg/month	Milk transported per month	186,000	kg/month
BSG transported per month	15,000	kg/month	BSG transported per month	18,000	kg/month
Stadium grass transported per month	18,000	kg/month	Concentrate transported per month	36,000	kg/month
DDGS transported per month	1260	kg/month	Maize transported per month	165,000	kg/month
Co2 emissions urban delivery truck	0.307	g Co2/kg-km	CO2 emissions long haul tractor trailers	0.057	gCo2/kg-km
C02 emissions per km electric car	99	g Co2/km	C02 emissions per km electric car	99	g Co2/km

Table 3.11: Comparison with Baseline: Circular Action, Eliminate Transport to Processing Facility

Circular Action: Eliminate Transport to a Processing Facility, Comparative Indicator			
Indicator	**Formula**		
% reduce carbon emissions for transportation	$\frac{\text{CO2 emissions}_{\text{Baseline}} - \text{CO2 emissions}_{\text{FF}}}{\text{CO2 emissions}_{\text{Baseline}}} \times 100$(3.15)		
Parameters Used to Calculate Indicator	*Amount FF*	*Amount Baseline*	*Unit*
To Normalize: Milk produced	24.00	26.96	L/day
To Normalize: Number of cows	30	230	cows
CO_2 emissions from transport	3.76	4.93	kg CO_2

Circular Action Indicators: Using Recycled Feed Crop

The final set of indicators focuses on the FF using recycled feed crops. For % recycled feed crop, FF was assumed to be 100% because none of the feed sources used are grown for the purpose of being animal feed. The feed sources were known for the baseline, so this indicator was used for both accessing the FF's performance and comparing to the baseline. Feed efficiency was calculated for the FF only to measure milk productivity in relation to the dry matter of the feed to see how using recycled feed can impact production. This was done using an online calculator of energy-corrected milk yield. Inputs for the calculator include milk fat and protein percentage, and amount of milk produced. The DW was also needed but was known from the feed data given by the FF. There was no data for the baseline expressing milk fat and protein percentages so this indicator was not calculated for the baseline, but standards for feed efficiency exist in literature that were used to compare with the FF.

The feed cost and land use indicators are the basis for two comparisons: % Feed cost reduction and % Land use reduction. For calculating feed cost, a mixture of literature and info from the FF was used and compared with the baseline's feed. This data was difficult to acquire, so a mixture of sources including farming blogs in the UK were considered. That being said these results should be taken as an estimation. Land use was calculated considering only the land used for grazing and growing crops (in the baseline's case). To determine land use for the baseline, the yield per hectare of the feed crops grown was used and added to the grazing land reported in the survey. Only the grazing area for the FF was considered for land use because the majority of the farm is on water. See table 3.12 for detailed procedures.

Table 3.12: Using Recycled Feed Crop: Indicators, Parameters, Units, and Formulas

<table>
<tr><th colspan="6">Circular action: Using Recycled Feed Crop</th></tr>
<tr><th>Indicator</th><th colspan="5">Formula</th></tr>
<tr><td>Recycled Feed</td><td colspan="5">$\frac{\text{Recycled feed}}{\text{Total feed input}} \times 100(3.16)$</td></tr>
<tr><th colspan="3">Data Used to Calculate Indicator(FF)</th><th colspan="3">Data Used to Calculate Indicator(Baseline)</th></tr>
<tr><td>Parameter</td><td>Amount</td><td>Unit</td><td>Parameter</td><td>Amount</td><td>Unit</td></tr>
<tr><td>Recycled Feed</td><td>100</td><td>%</td><td>Beer Residue Amount</td><td>5400</td><td>kg DW/month</td></tr>
<tr><td></td><td></td><td></td><td>Total feed</td><td>109,307.1429</td><td>kg DW/month</td></tr>
<tr><th>Indicator</th><th colspan="5">Formula</th></tr>
<tr><td>Land use</td><td colspan="5">$\sum_i \left(\frac{\text{Weight of feed}_i}{\text{Yield per hectare}_i}\right) + \text{Grazing land}(3.17)$</td></tr>
<tr><th colspan="3">Data Used to Calculate Indicator(FF)</th><th colspan="3">Data Used to Calculate Indicator(Baseline)</th></tr>
<tr><td>Parameter</td><td>Amount</td><td>Unit</td><td>Parameter</td><td>Amount</td><td>Unit</td></tr>
<tr><td>To Normalize: Milk produced</td><td>24</td><td>L milk/cow/day</td><td>To Normalize: Milk produced</td><td>26.96</td><td>L milk/cow/day</td></tr>
<tr><td>To Normalize: Number of cows</td><td>30</td><td>cows</td><td>To Normalize: Number of cows</td><td>230</td><td>cows</td></tr>
<tr><td>Total grazing area</td><td>0.18</td><td>ha</td><td>Beets yield per hectare</td><td>50,000</td><td>kg DM/ha</td></tr>
<tr><td></td><td></td><td></td><td>Silage grass yield per hectare</td><td>5000</td><td>kg DM/ha</td></tr>
<tr><td></td><td></td><td></td><td>Maize yield per hectare</td><td>45,000</td><td>kg /ha</td></tr>
<tr><td></td><td></td><td></td><td>Concentrate yield per hectare</td><td>45,000</td><td>kg/ha</td></tr>
<tr><td></td><td></td><td></td><td>Beets weight of feed</td><td>94,900</td><td>kg DW/year</td></tr>
<tr><td></td><td></td><td></td><td>Silage grass weight of feed</td><td>172,380</td><td>kg DW/year</td></tr>
<tr><td></td><td></td><td></td><td>Maize weight of feed</td><td>2,007,500</td><td>kg/year</td></tr>
<tr><td></td><td></td><td></td><td>Concentrate weight of feed</td><td>438,000</td><td>kg/year</td></tr>
<tr><td></td><td></td><td></td><td>Total grazing area</td><td>85</td><td>ha</td></tr>
<tr><th>Indicator</th><th colspan="5">Formula</th></tr>
<tr><td>Feed cost</td><td colspan="5">$\sum_{i=1}^{n}(\text{Unit Cost of Feed Ingredient}_i \times \text{Amount of Feed Ingredient}_i)(3.18)$</td></tr>
</table>

Data Used to Calculate Indicator(FF)			**Data Used to Calculate Indicator(Baseline)**		
Parameter	*Amount*	*Unit*	*Parameter*	*Amount*	*Unit*
To Normalize: Milk produced	24	L milk/cow/day	To Normalize: Milk produced	26.96	L milk/cow/day
To Normalize: Number of cows	30	cows	To Normalize: Number of cows	230	cows
BSG amount	15,000	kg/month	BSG amount	18,000	kg/month
DDGS amount	1260	kg/month	Silage grass amount	16,714.29	kg/month
Grass Amount	18,000	kg/month	Maize amount	165,000	kg/month
BSG unit cost	0.035	euro/kg	Feed beets amount	39,000	kg/month
DDGS unit cost	0	euro/kg	Concentrate amount	36,000	kg/month
Grass unit cost	0.12	euro/kg	BSG unit cost	0.035	euro/kg
			Silage grass unit cost	0.059	euro/kg
			Maize unit cost	0.048	euro/kg
			Feed beets unit cost	0.052	euro/kg
			Concentrate unit cost	0.37	euro/kg
Indicator	**Formula**				
Feed efficiency	$\frac{\text{Energy corrected milk yield}}{\text{Dry matter intake}}$(3.19)				
Parameter	*Amount*	*Unit*			
Milk yield (kg)	24	kg/day/cow			
ECM	27.18	kg			
DM intake	28.66	kg			

3.5. System Testing

To assess uncertainties within major assumptions several methods were utilized. The biggest variables of interest to be assessed for sensitivity and uncertainty were those assumed to close the water, nutrient, or energy balances. In this analysis, three variables were identified that were assumed to close a balance but were based on literature. To test sensitivity the values from literature were used in the model to see the impact on the balance. This was especially relevant for the amount of N and P in manure within the nutrient balance.

To start the nutrient balance a feed composition was chosen which excluded the ‘treats’ that are extras added into the feed from grocery store waste. To test the sensitivity of the feed composition, and check that excluding the ‘treats’ did not deeply impact the model, the nutrient amounts with the N and P content of the treats were added into the model and compared with the original feed composition. To compare the two, the ‘% not balanced’(equation 3.20) was calculated for both models.

$$\left(\frac{\text{Nutrient Balance}}{\text{Nutrient Input}}\right) \times 100\% \tag{3.20}$$

For the electricity balance, the influence of seasonality on the averages used was of interest. The network consumption data was only available for the entire year so seeing seasonal differences was difficult. The solar production, however, was given monthly and averaged. In order to view uncertainties from averaging the data, data for each season was selected and compared to the average. It is important to note that data for an entire year does not exist so the average used is for 7 months only (from May to December). This data was assumed to be representative of all four seasons. To compare the individual months to the average, the standard deviation was calculated to obtain Z scores for each season. A Z score indicates how many standard deviations an individual value is from the mean (equation 3.21). The Z scores obtained were then used to discuss the impact of seasonality on the accuracy of the energy usage used in the balance for the farm.

$$z = \frac{X - \mu}{\sigma} \tag{3.21}$$

where:

X is the individual value,

μ is the mean of the dataset,

σ is the standard deviation of the dataset.

The largest assumption made in this analysis was the cooling water use in the milk processing center. Originally this assumption was ‘verified’ by a simple experiment to estimate the flow rate from a nearby tap. Since then, based on the preliminary results of this thesis, a flow meter has been installed. Data from the flow meter was then used to better validate the assumption and discuss uncertainties brought about by using an assumed value.

Finally, uncertainties within calculated indicators were identified and discussed. Uncertainties were identified by looking at data used for the indicators and whether it was assumed from literature, measured, or assumed by the farm. The indicators with the most uncertainty were identified and recommendations for making them more certain were given. Uncertainty and data sources for the water, nutrient, and energy balances were already identified in the color code of the Sankey diagrams.

3.6. Improvement Scenario Identification

Once the circularity analysis was complete and circularity gaps were identified, different scenarios for improvement were identified. The improvement area was derived from the circularity gaps directly, and the solutions and recommendations were derived based on knowledge of water treatment, nutrient recovery, literature, and advice from faculty members.

Once several solutions were identified, the scenarios were brought to the thesis committee and the FF to choose the most feasible ideas to consider as a scenario to add to the original model and indicator calculations. Instead of fully designing one solution, it was decided to present four solution scenarios and include information and data regarding each scenario’s pros and cons as well as its impact on the water and nutrient flows and circularity indicators.

3.7. Scenario Integration

3.7.1. Update Cooling System

For each scenario, two primary methods were of focus to relay the feasibility and usefulness of each solution. The first method focuses on gathering information relevant to the feasibility of implementation on the farm as well as needed maintenance in the future. From this information, recommendations can be made.

The first scenario is to change the water source from the grid to river water once-through cooling (OTC) in the milk processing center. This would involve pumping water from the river to be used to cool the compressor and then the water would be returned to the source. For this solution, the primary concern for its feasibility is the quality of the river water and the scaling and corrosion risks it may pose in the system. To assess the quality of the water and its risk, water quality data from Rijkswaterstaat was obtained for the Nieuwe Maas near the FF [46]. This data includes relevant ions, and parameters such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), and dissolved oxygen (DO). To more accurately assess the risk of corrosion, the Ryznar index was calculated using the Lenntech calculator to compare both the Nieuwe Maas water and tap water. The calculator requires the pH, TDS, calcium, and bicarbonate ions. These parameters were taken from Evides' water quality check platform using the zip code of the FF. The ions were then input into the platform PHREEQC to obtain modeled saturation indices (SI) to determine the risks of precipitates forming (For input code see Appendix C.1, Figure C.1). The ion concentrations were also compared to Dutch standards from the Drinking Water Directive to compare to the tap water currently being used. Based upon these analyses recommendations for the feasibility of the solution and required maintenance were made. See Appendix C.2.

The second method to evaluate this scenario is to add it to the indicator calculations to quantify its possible impact on the circularity and performance of the FF. For updating the cooling system the indicator groups impacted are 'Waste Minimization' and 'Using a Non-Finite Water Source'. For 'Waste Minimization', both waste index and waste utilization index indicators were recalculated to account for having less wastewater because the water will be returned to the source. In this scenario, the only wastewater from milk processing is from glycol cooling, cheese washing, and cleaning. Also recalculated was the 'Using a Non-Finite Water Source' indicator which evaluates the self-sufficiency in terms of water for the farm. With a large amount of water being obtained via the river, (internally derived) this indicator will be impacted.

To quantify the numerical change from the base model to the scenarios the % difference and absolute difference were calculated via the equations 3.22 and 3.23 below. The updated parameters used to recalculate the indicators relevant to this scenario are displayed in tables 3.13 and 3.14 below.

$$\text{Percent Difference} = \left(\frac{|\text{Calculated base model indicator} - \text{Calculated indicator for scenario}|}{\text{Calculated base model indicator}}\right) \times 100\% \quad (3.22)$$

$$\text{Absolute Difference} = |\text{Calculated base model indicator} - \text{Calculated indicator for scenario}| \quad (3.23)$$

Table 3.13: Updated parameters for 'Waste Minimization' indicators with an updated cooling system

Circular Action: Waste Minimization		
Indicator	**Formula**	
Waste index	$\frac{\text{Mass of waste}}{\text{Mass of resources used}} \times 100$(3.11)	
Data Used to Calculate Indicator(FF): With Updated Cooling System		
Weight of the liquid fraction of manure	1265.60	kg/day
Waste water milk processing (cleaning, glycol, cheese rinse)	2800.00	kg/day
Feed input	1142.00	kg/day
Water input	19,030.65	kg/day
Indicator	**Formula**	
Waste utilization index	$\frac{\text{Utilized waste}}{\text{Utilized waste+Total waste produced}} \times 100$(3.12)	
Data Used to Calculate Indicator(FF): With Updated Cooling System		
Weight of the liquid fraction of manure	1265.60	kg/day
Weight of the solid fraction of manure	542.40	kg/day
Waste water from milk processing (cleaning, glycol, cheese rinse)	2800.00	kg/day

Table 3.14: Updated parameters for 'Using a Non-Finite Water Source' indicators with an updated cooling system

Circular Action: Using a Non-Finite Water Source		
Indicator	**Formula**	
% water self-sufficiency	$\frac{\text{Internally derived water used}}{\text{Total water used}} \times 100$(3.13)	
Data Used to Calculate Indicator(FF): With Updated Cooling System		
Parameter	*Amount*	*Unit*
Rainwater	513.70	L/day
Water from river	13,123.15	L/day
Total water used	19,030.65	L/day

3.7.2. Add Desalination

The second scenario aims to increase the self-sufficiency of the farm and give the FF insight into the feasibility of adding desalination. Desalination technologies are something the FF has expressed interest in within the Water Mining objectives. The FF is particularly interested in desalination which has a low energy trade-off. They have partnered with the company Rainmaker which specializes in low energy desalination and have installed a pilot at the FF. The pilot is not running currently, but using membrane distillation with manure as a heat source. This technology is very interesting and novel, but the pilot has a very small capacity. Minimal data was available for this system. A larger membrane distillation system may also be a possibility for the future, and Rainmaker has installed larger systems at other sites, but such systems run on wind and solar energy. It is unknown if a larger system could use manure as the sole heat source. Since there is much uncertainty and a lack of data surrounding this system other options were considered. The rainmaker machine was still included in indicator recalculations to show its impact. To meet the FF capacity, more traditional membrane technologies were investigated. To understand energy costs and the impact on permeate quality with this treatment, an analysis of the membrane projection program WAVE was conducted.

To configure the model in WAVE the same water quality data used for the cooling scenario was used (see table C.3). To run WAVE the ions have to be balanced and the data used was not, likely because of varying chloride and sulfate concentrations. Auto balance was used which increased the chloride concentration substantially. The increase, however, is not implausible as the chloride concentration has reached these levels on occasion in the five-year data presented by Rijkswaterstaat. This assumption may impact the scaling risks in the membrane and the risk of corrosion and the projection should be taken as only a first investigation not as a final design.

After researching both reverse osmosis (RO) and nanofiltration (NF) several advantages were found for using NF instead of RO. Since the water quality is rather high and the main concerns are hardness and salt concentrations RO is likely not necessary. NF can remove hardness and chlorine at high efficiencies and includes advantages such as low operation pressure, low energy consumption, and higher output [47]. For these reasons, an NF membrane was chosen for the projection.

The chosen membrane for the projection is Dupont NF90-2540 it is advertised to remove high percentages of salts, nitrate, and hardness at a low operating pressure [48]. It has a lower flow rate than other models and was chosen because the production of around 20 m^3/day is quite low for membranes. 20 m^3/day is more water than the FF needs (they currently use 19.2 m^3/day), and a projection for a low production was attempted (for example excluding the OTC water) but the needed flow rates were too small and the program would not converge. Once the influent flow rate and membrane were chosen, the number of stages, elements, and pressure vessels (PV) were chosen and tested using trial and error until no design limits were crossed after running the projection. The chosen configuration uses two stages. The first has two PV with 6 elements each and the second has one PV with 6 elements (total 18 elements). Other arrangements may be possible. The projection report gives the permeate water quality as well as utility and chemical cost estimates which contribute to the feasibility of the approach. See the primary parameters of the model below (table 3.15).

Table 3.15: Summary of WAVE model parameters

Parameter	Amount	Unit
Membrane	NF90-2540	
Raw feed to NF system	1.28	m^3/h
Concentrate flow rate	0.45	m^3/h
Number of elements	18	units
Number of stages	2	stages

To quantify the impact of this scenario on the indicators some ‘Using Renewable Energy’ were recalculated assuming the energy usage from the projection (table 3.16). Water self-sufficiency from the ‘Using a Non-Finite Water Source’ indicators was also recalculated but not presented in the table below because it was assumed to be 100%. Percent difference and absolute difference were also calculated using equations 3.22 and 3.23. Table 3.16 below outlines the recalculation procedure and updated parameters used to make the calculations for this scenario.

Table 3.16: Updated parameters for ‘Using renewable energy’ indicators with NF scenario

Circular action: Using Renewable Energy		
Indicator	**Formula**	
Electrical energy self sufficiency	$\frac{\text{Internally derived energy used}}{\text{Total energy used}} \times 100$(3.5)	
Data Used to Calculate Indicator With NF		
Parameter	*Amount*	*Unit*
Average solar energy produced in a year	0.0071	kWh/L milk
Energy demand (solar+grid+NF)	0.082	kWh/L milk
Indicator	**Formula**	
Circular process energy intensity	$\frac{\text{Fossil energy}+\text{Renewable energy}-\text{Internally Derived energy}}{\text{Mass of product}+\text{Mass of recovered product}}$(3.6)	
Data Used to Calculate Indicator(FF)		
Fossil energy	32.45	kWh/day
Renewable energy	21.63	kWh/day
Internally derived (solar energy)	5.11	kWh/day
Mass of product (milk)	743.76	kg/day
Mass of recovered product (manure)	271.20	kg/day

3.7.3. Update Current Urine Treatment System

This scenario is derived from the circularity gap found from wasting the liquid fraction of manure in the current urine treatment design. The current urine treatment system is composed of four intermediate bulk containers (IBC). The first is an aerobic combustion container to convert organic matter (OM) to CO_2 and water. The second is for settling. The third contains nitrifying bacteria (NH_4 to NO_2 to NO_3), and the fourth is a second settling tank. This system removes OM and converts ammonia to nitrate, but produces water that is still full of nitrate and phosphorus (there is no precipitation step so most P is in the water). This makes the options for usage limited to possibly for the vertical farm (but should first be tested), or another agricultural use (if nutrients are monitored). Figure 3.3 shows the current system in place at the farm. This system is not currently operational due to clogging.

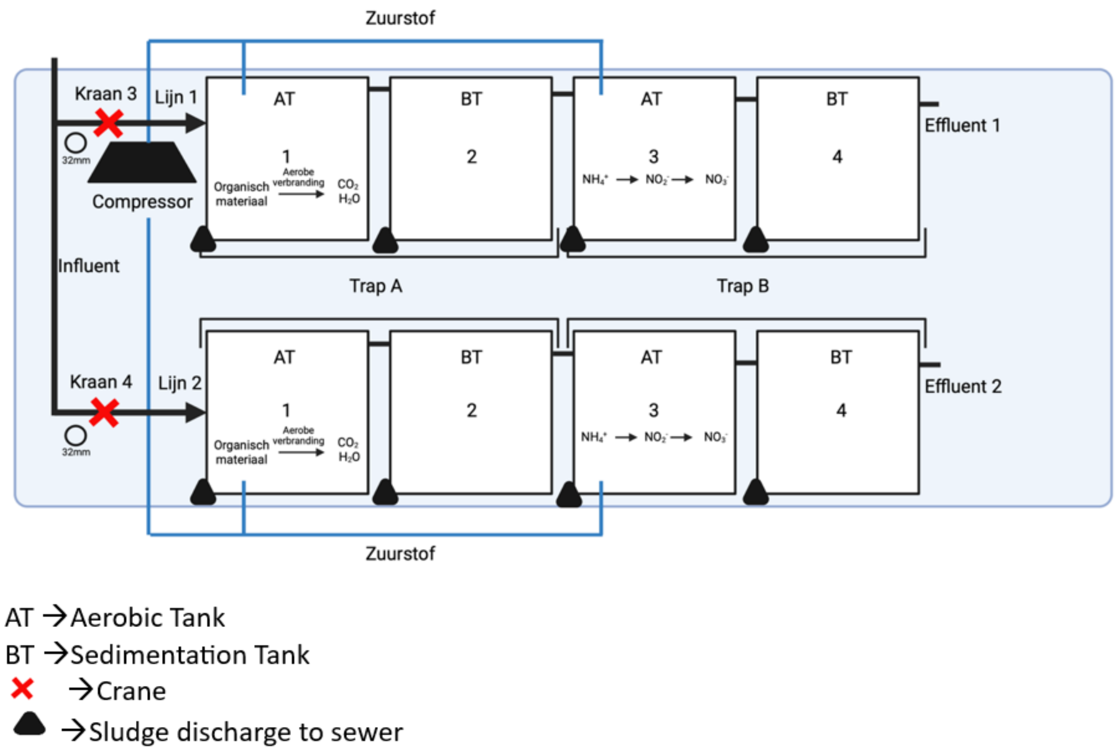

Figure 3.3: Current Urine Treatment System [From FF]

The primary goal for an updated treatment system was to make the treated water more usable in other parts of the farm such as for cleaning or the vertical farm. To make the water more usable further treatment for nutrient removal is likely necessary. Nutrient recovery would be the ideal solution, but given the scale and resources of the FF, nutrient recovery may be difficult. To assess of feasibility of further treatment technologies a literature study focusing on denitrification processes and P precipitation as P salts or struvite was conducted. The goal of the literature study was to understand the basics of processes currently used by dairy farms for P precipitation and denitrification to assess the feasibility for the FF. The hope is to be able to recommend technologies for the farm to investigate further.

Efficiencies from the literature study were then used to recalculate indicators from the 'Water and Nutrient Recovery', 'Waste Minimization', and 'Using a Non-Finite Water Source' indicator groups to assess the potential impacts of the proposed solutions on the circularity indicators. The amount of water that can be recovered is assumed to be 99% of influent and 1% is assumed to be sludge [49]. The N converted to N_2 is assumed to be waste. Percent difference and absolute difference were also calculated using equations 3.22 and 3.23. Tables 3.17, 3.18, and 3.19 below outline the calculation procedure and parameters for the updated indicators for this scenario.

Table 3.17: Updated parameters for ’Water and Nutrient Recovery’ indicators with updating urine treatment scenario

Circular action: Water and Nutrient Recovery		
Indicator	**Formula**	
P recovery rate	$\frac{\text{Amount of P recovered (In cow, in milk, in manure)}}{\text{Total entering amount of P}} \times 100 (3.9)$	
Data Used to Calculate Indicator(FF): Update Current Urine Treatment System		
Parameter	*Amount*	*Unit*
P retained in cow	0.39	kg P/day
P in milk	0.34	kg P/day
P in solid fraction of manure	3.82	kg P/day
P input (in feed)	5.61	kg P/day
Indicator	**Formula**	
Water recovery in products	$\frac{\text{Amount of water recovered in products}}{\text{Total entering amount of Water}} \times 100 (3.10)$	
Data Used to Calculate Indicator(FF): Update Current Urine Treatment System		
Parameter	*Amount*	*Unit*
Water in solid fraction of manure	325.44	L/day
Recovered water from urine treatment	1252.94	L/day
Water retained in cow	969.25	L/day
Water in milk	626.40	L/day
Total water usage	19,030.65	L/day

Table 3.18: Updated parameters for 'Waste Minimization' indicators with updating urine treatment scenario

Circular Action: Waste Minimization		
Indicator	**Formula**	
Waste index	$\frac{\text{Mass of waste}}{\text{Mass of resources used}} \times 100(3.11)$	
Data Used to Calculate Indicator(FF): With updated urine treatment		
Parameter	*Amount*	*Unit*
Wastewater from milk processing	15,923.15	kg/day
N released as N_2	5.37	kg/day
Feed input	1142.00	kg/day
Water input	19,030.65	kg/day
Indicator	**Formula**	
Waste utilization index	$\frac{\text{Utilized waste}}{\text{Utilized waste+Total waste produced}} \times 100(3.12)$	
Data Used to Calculate Indicator(FF): With updated urine treatment		
Parameter	*Amount*	*Unit*
Weight of the water from liquid fraction after treatment	1252.94	kg/day
Weight of the solid fraction of manure	542.40	kg/day
Weight of sludge produced	12.66	kg/day
N released as N_2	6.71	kg/day
Wastewater from milk processing	15,923.15	kg/day

Table 3.19: Updated parameters for 'Using a Non-Finite Water Source' indicators with updating urine treatment scenario

Circular Action: Using a Non-Finite Water Source		
Indicator	**Formula**	
% water self sufficiency	$\frac{\text{Internally derived water used}}{\text{Total water used}} \times 100(3.13)$	
Data Used to Calculate Indicator(FF): With updated urine treatment		
Parameter	*Amount*	*Unit*
Rainwater	513.70	L/day
Water from urine treatment	1252.94	L/day
Total water used	19,030.65	L/day

3.7.4. Connecting the Urine Treatment to the Vertical Farm

The water and nutrient needs were also assessed for the vertical farm in order to explore the possibility of connecting the dairy system and vertical farm by using waste products from the dairy system as water and nutrient sources for the vertical farm. This was done by comparing the amount of water and nutrients that are produced from the liquid fraction of manure with the needs of the vertical farm. A calculation to determine how large the vertical farm would need to be to use all the water from the liquid fraction of manure was calculated.

To determine the water and needs for the vertical farm, the crop micro greens which the FF grows was used as a benchmark crop and the amount of water and nutrients needed per day was determined based on how much water and nutrients micro greens need in a day. This was then compared to the water and nutrients produced from the urine treatment system. The water needed was relatively easy to find in literature, but nutrients were not as straightforward. After the proposed treatment, it is assumed that the nutrients left in the water are minimal so only the water was considered. It will be useful to test the treated water for N and P content after treatment so it is known exactly how much nutrients are going into the crops.

To determine water produced after treatment the weight of the liquid fraction (kg/day), and the amount of sludge produced (kg/day). The amount of water needed for growing microgreens was determined from literature. The water produced by the urine treatment was divided by the water needed to determine how much larger the vertical farm would need to be to match water needs. Equations 3.24 and 3.25 below were used. Table 3.20 summarizes the parameters used to calculate the farm size and factor of increase.

$$\text{Farm Size}\,(m^2) = \frac{\text{Amount of Water Produced}\,(L)}{\text{Water Need per Square Meter}\,(L/m^2)} \tag{3.24}$$

$$\text{Factor of Increase} = \frac{\text{Required Farm Size}\,(m^2)}{\text{Current Farm Size}\,(m^2)} \tag{3.25}$$

Table 3.20: Parameters needed to determine the amount of water produced by urine treatment and water requirement for vertical farm

Data Used to Calculate		
Parameter	*Amount*	*Unit*
Weight of liquid fraction	1265.60	kg/day
% sludge [49]	1	%
Density of water	1	kg/L
Microgreen water need [50]	2	L/m^2
Current farm size (farm in construction)	140	m^2

3.7.5. Anaerobic Treatment of Manure

The final scenario involves investigating using anaerobic treatment for the liquid fraction of manure. In literature, anaerobic digestion (AD) is often used for waste management in dairies. For managing configurations most similar to the FF, it is often used as a pretreatment step before manure is separated and has been shown to increase separation efficiencies by increasing nutrient mineralization [51]. Most importantly AD produces biogas which can be used to produce electricity. For this scenario, the primary focus was to highlight the pros and cons for the FF to install an AD and to estimate the potential biogas production if an AD was installed.

To determine the pros and cons of this technology, literature using similar waste management techniques was investigated. To estimate biogas production, conversions from literature from m^3 slurry to m^3 biogas, and from m^3 biogas to kWh were utilized [52], [53]. Once the biogas production was estimated, the indicators for 'Using Renewable Energy' were recalculated to assess the potential impact on energy projection on the farm. Percent and absolute differences were also calculated using equations 3.22 and 3.23. The updated parameters for the updated indicators are displayed in table 3.21 below.

Table 3.21: Updated parameters for 'Using Renewable Energy' indicators with anaerobic treatment scenario

Circular Action: Using Renewable Energy		
Indicator	**Formula**	
Electrical energy self sufficiency	$\frac{\text{Internally derived energy used}}{\text{Total energy used}} \times 100$(3.5)	
Data Used to Calculate Indicator(FF): With an AD		
Parameter	*Amount*	*Unit*
Average solar energy produced	5.11	kWh/day
Total energy demand (grid+solar)	56.69	kWh/day
Biogas conversion [52]	20	m^3 biogas/m^3 slurry
Slurry Amount	1.81	m^3/day
kWh conversion [53]	6.00	kWh/m^3 biogas

4

Results

4.1. System Development

4.1.1. Goal and Assessment Level

The identified goal of the circularity analysis is to quantify the circularity initiatives within the FF dairy production process as outlined by the research question. Targeted problems to address in the analysis include circularity gaps and system losses. The assessment level for analysis is process level.

4.1.2. Resource Flows

For individual process flows derived for water, energy, and nutrient balance see Appendix B (Figures B.1, B.2, B.3). Figure 4.1 below describes the primary process flows for milk production, milk processing, and waste management.

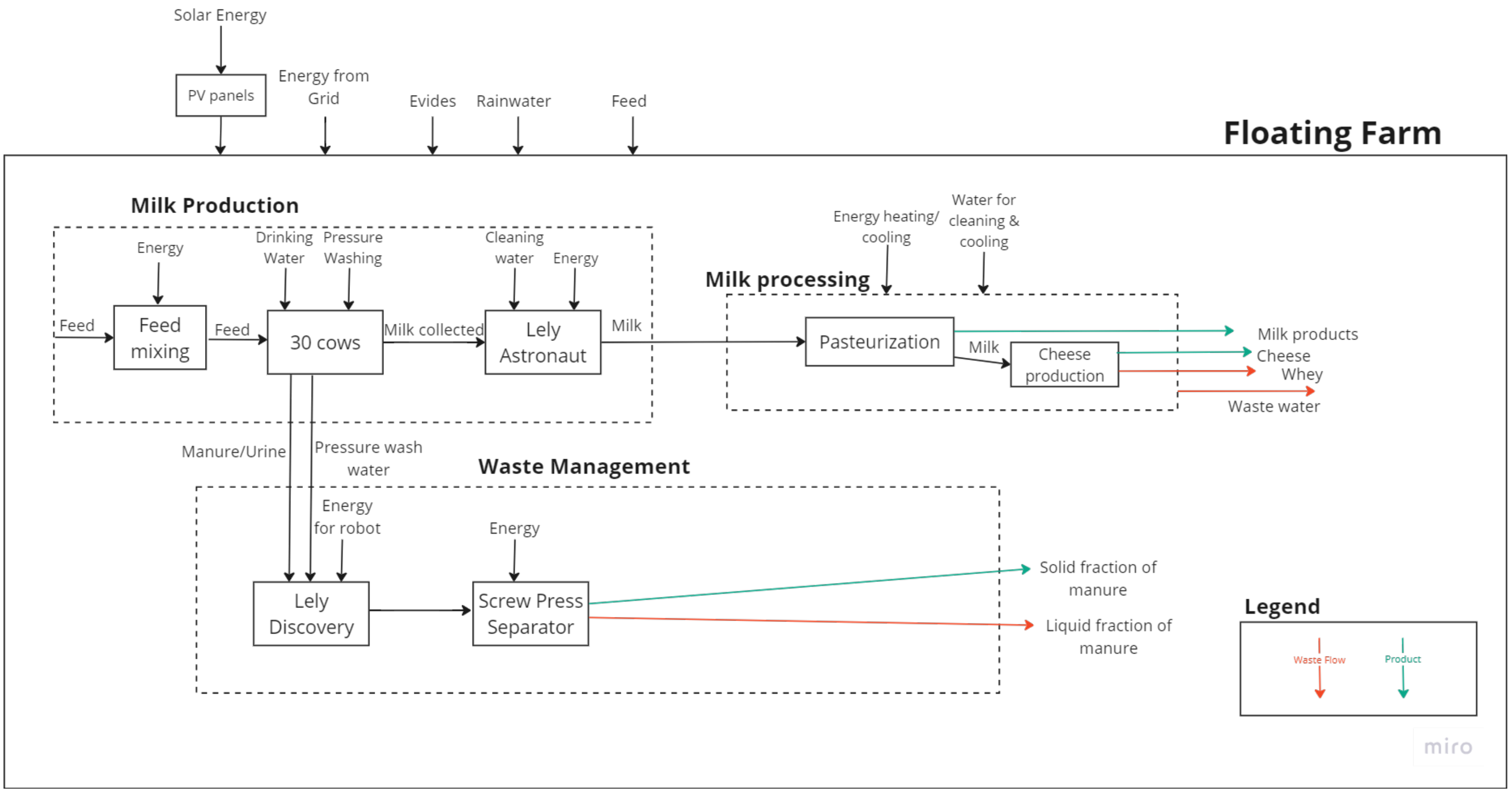

Figure 4.1: Whole Farm Process Diagram

4.1.3. Circular Actions

Six circular actions were identified from the farm regarding circular improvements in areas of water management, energy use, waste management, transportation, and feed. Table 4.1 below outlines the chosen actions and explains the relevance the the FF.

Table 4.1: Identified circular actions and the explanation for how they apply to the FF

Action	**Explanation**
Using renewable energy	FF uses floating solar panels
Water and nutrient Recovery	FF sells manure as a biofertilizer and uses urine treatment to save nutrients Water is recovered in products (milk and manure)
Waste minimization	Solid manure is sold to a third party and used instead of wasted
Using a non-finite water source	The FF has a rainwater collection system
Eliminate transportation to processing facility	The processing center is connected to the milk production so there is no transport to a secondary location
Using recycled feed crop	The FF uses all recycled feed such as bierbostel and grass cuttings from the stadium

4.2. Indicator Identification

From the circular actions identified, six indicator sets were established. The first set of indicators, based on the circular action ‘Using Renewable Energy’, is straightforward. They were taken from WP8 and include indicators to quantify the FF’s energy self-sufficiency and circular process energy intensity. These indicators measure how much internal energy the FF uses in relation to total use and how much of the energy used is circular.

The ‘Water and Nutrient Recovery’ indicators were also simple. They were taken directly from WP8, but similar or identical indicators are present in Velasco-Muñoz, Mendoza, Aznar-Sánchez, *et al.* [24] in a more agricultural context. These indicators include measures of water recovery in products, N recovery, and P recovery.

The indicators for the ‘Waste Minimization’ circular action are also from WP8 and quantify the waste flows with respect to the whole system. The first indicator, waste index, compares the mass of waste to the resources input, and the second, waste utilization index, focuses on the waste that is utilized as a product.

The indicator for ‘Using a Non-finite Water Source’ is similar to the energy indicators and assesses the self-sufficiency of the farm in terms of water use. It was also derived from WP8.

The indicators for ‘Eliminate Transport to a Processing Facility’ were not taken directly from WP8 but were inspired by WP8 indicators and adapted to fit the agricultural context of the FF. The purpose of this indicator is to evaluate whether the FF’s urban farming model reduces CO_2 emissions from transport compared to the baseline farming model.

The final set of indicators is for the circular action ‘Using Recycled Feed Crop’. These indicators were primarily derived from Velasco-Muñoz, Mendoza, Aznar-Sánchez, *et al.* [24]. Feed impacts many processes on the farm, and these indicators reflect that by measuring several aspects regarding feed crops. For this indicator set, some comparative indicators were derived to compare the FF to the baseline.

Table 4.2 below outlines the indicators chosen for each circular action and indicates whether it is calculated for the FF, both FF and baseline, or is a comparative indicator.

Table 4.2: Identified indicators for each circular action

Using Renewable Energy	**Water and Nutrient Recovery**	**Waste Minimization**
Electrical energy self sufficiency (FF & Baseline)	N recovery rate (FF)	Waste Index (FF)
Circular process energy intensity (FF & Baseline)	P recovery rate (FF)	Waste utilization index (FF)
Electrical energy demand minimization w/o processing energy (Comparative Indicator)	Water Recovery in products (FF)	
Using a Non-Finite Water Source	**Eliminate Transport to a Processing Facility**	**Using Recycled Feed Crop**
% water self sufficiency (FF)	Co2 emissions from transport (FF & Baseline)	% recycled feed (FF & Baseline)
	% reduced carbon emissions from transport (Comparative Indicator)	Land use (FF & Baseline)
		Feed cost (FF and Baseline)
		% reduction in land use (Comparative Indicator)
		% reduction in feed cost (Comparative Indicator)

4.3. Mass and Energy Balances

The mass and energy balances for the farm are visualized using Sankey Flow diagrams below. The data uncertainty/ source is visualized using the color code shown in Figure 4.2.

Figure 4.2: Color code for Sankey Labels based on data source and uncertainty

4.3.1. Nutrient Balance

In Figure 4.3, the N flows throughout the system are quantified. All the main processes within the scope are represented. Of the flows pictured, the losses are the NH_3 losses in the barn and storage, assumed based on Aguirre-Villegas, Besson, and Larson [34], the liquid fraction of the manure which is sent to urine treatment and then to the sewer (when operational), and the whey in the wastewater of milk processing. Due to the distribution of N between the liquid and solid manure streams, most of the N ends up in the liquid stream and is then wasted (44.7% of input). The whey stream is also a loss in this system; however, only 10% of the milk produced is used to make cheese, and only 0.16% of whey is nitrogen, making the waste stream only 0.55% of the input [54].

Figure 4.4 yields a similar result as the N mass balance with 61.8% of input P ending up in the liquid fraction of manure and eventually the sewer. The same ratio of P in liquid vs solid fraction was assumed as the N balance from the same source. The loss of whey is also almost negligible with 0.22% of the input being wasted as whey.

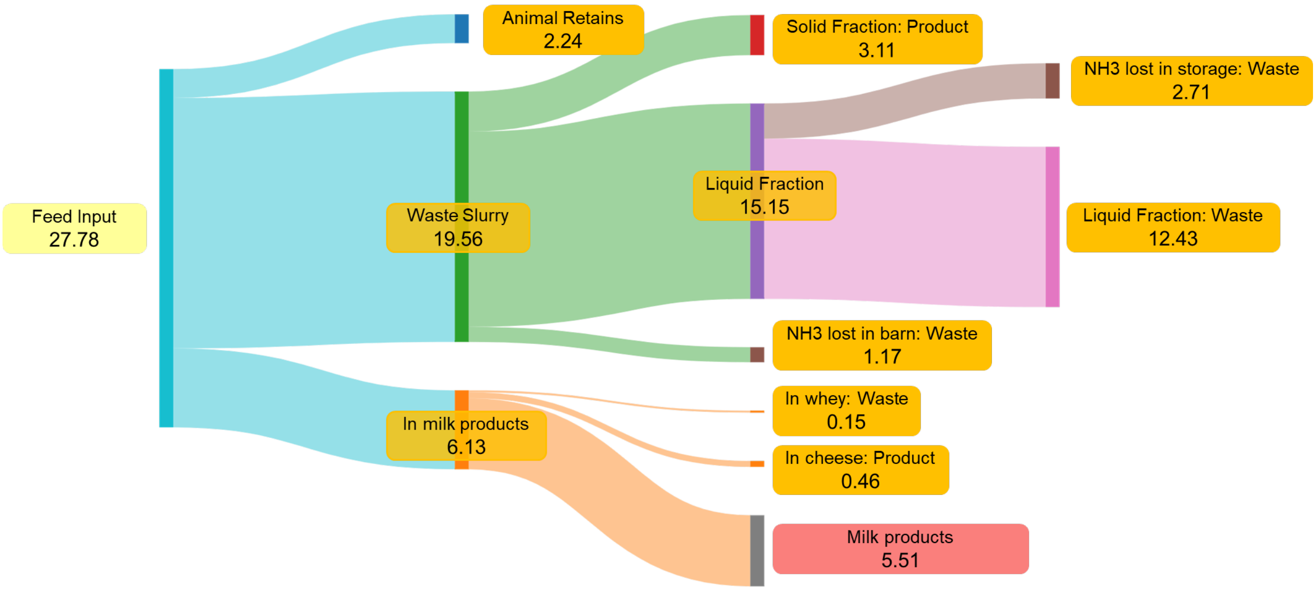

Figure 4.3: Nitrogen flows in g N/L milk

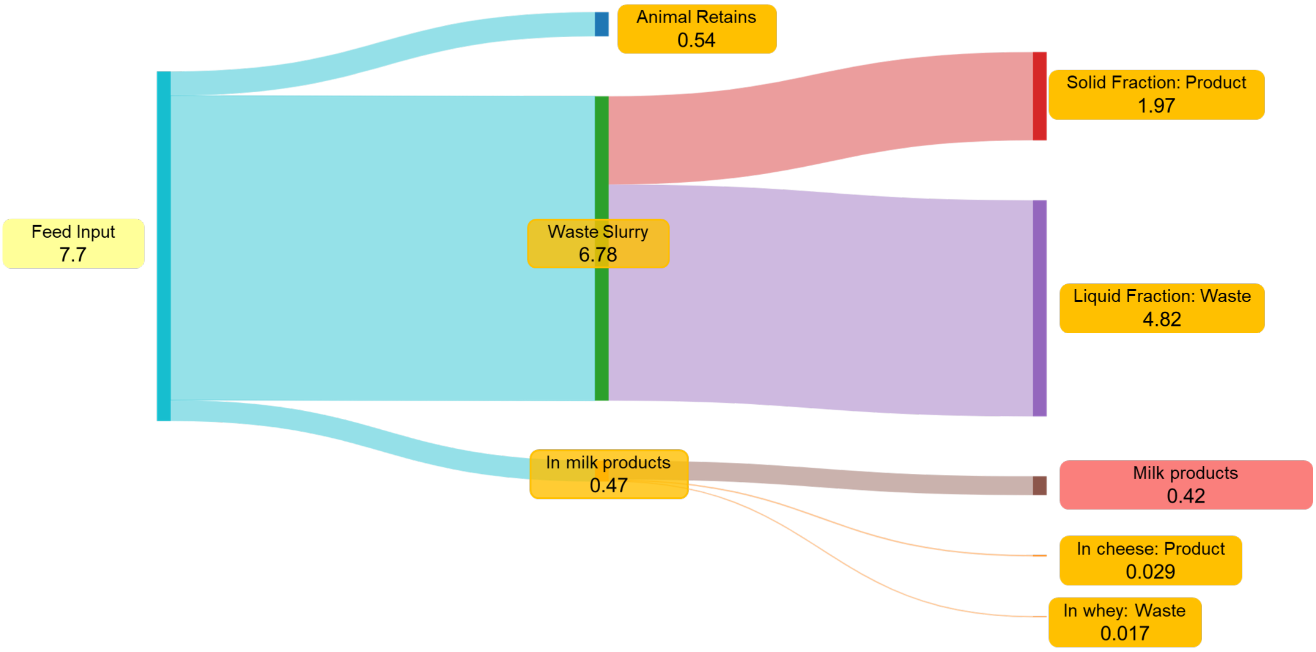

Figure 4.4: Phosphorus flows in g P/L milk

4.3.2. Electrical Energy Use

Figure 4.5 below shows the approximate electric energy flows for each process. From this diagram, it is obvious that most energy comes from the grid (see energy indicators below for more detailed comparisons of energy sources). The distribution may vary due to the many assumptions made and the lack of data present, but this balance is proportional to what would be expected based on literature and the energy use of other farms [41].

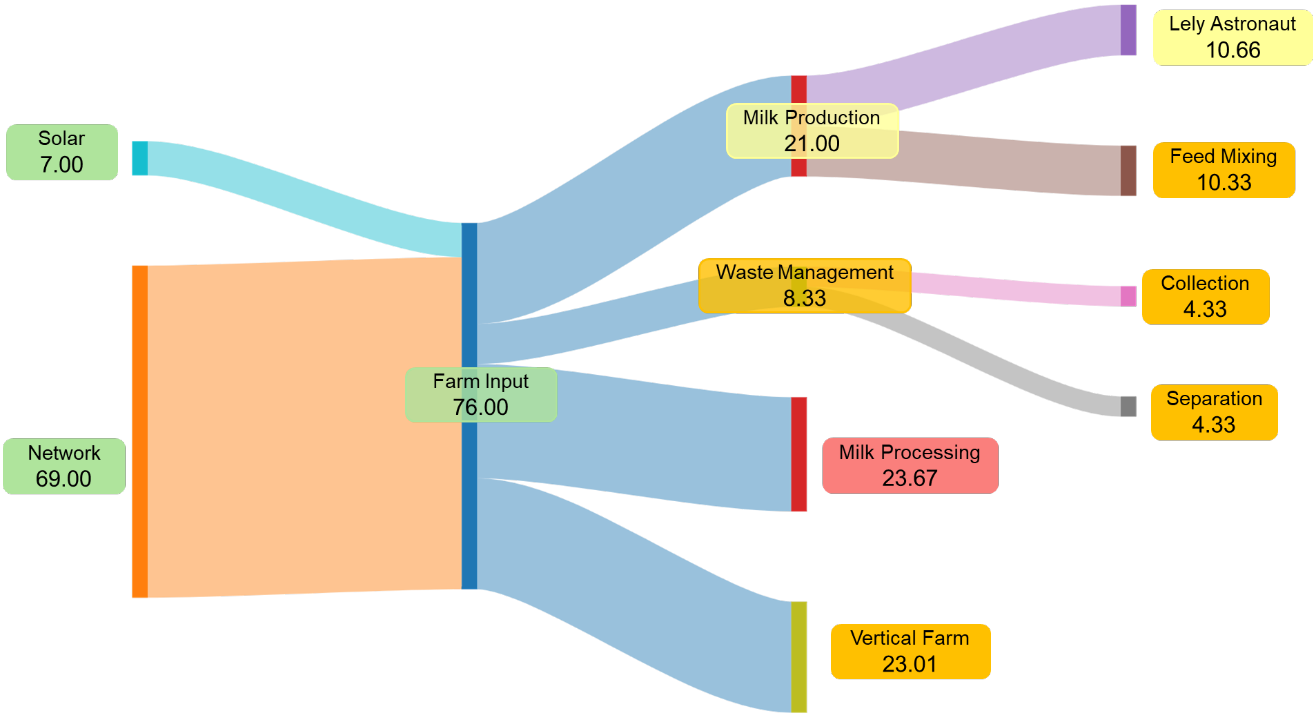

Figure 4.5: Electrical energy flows in Wh/L milk

4.3.3. Water Balance

Figure 4.6 depicts the water flows through the system based on inputs from Evides, rainwater collection, and water in feed. There is a very large amount of water used from the grid (more information can be found with the calculated indicators) and, in comparison, very little rainwater is collected. The water use in milk production is straightforward with no obvious gaps in circularity. The losses from production include water in urine and robot water. A large amount of water (22 L water/L milk or 87% of all usage on the farm) was estimated for milk processing. This disproportionate usage is likely due to the use of OTC for a compressor in the cooling system. Most, if not all, of the water used in processing ends up in the sewer even if it is still of high quality. A large gap in circularity was found in the cooling system of the milk processing center.

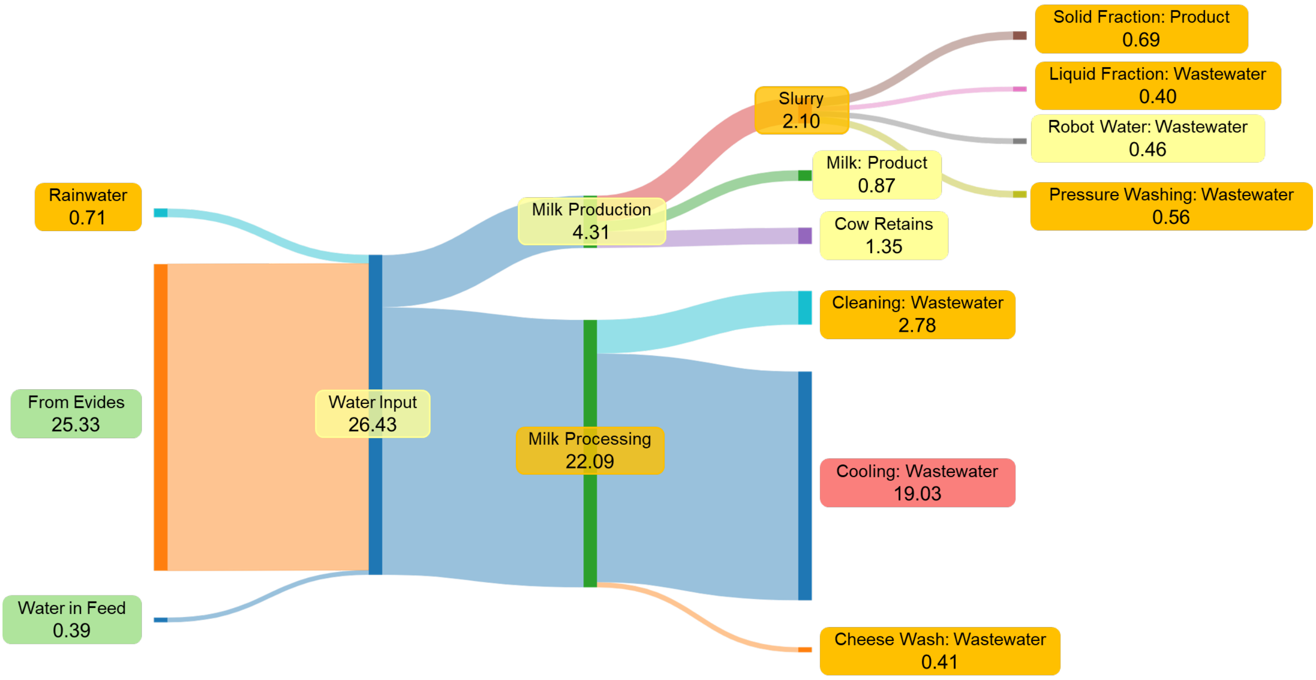

Figure 4.6: Water usage in L water/L milk

4.4. Indicator Calculations

4.4.1. Using Renewable Energy Indicators

The first set of indicators assesses the FF's claim that they are circular due to the solar panels installed to generate their own renewable energy. The indicators used assess self-sufficiency and energy use compared to the mass of the products. A separate comparative indicator compares the FF's energy demand to the baseline's.

The FF's self-sufficiency was calculated to be 9.36%. This is likely because the farm's capacity to produce solar energy is limited due to a lack of space for solar panels, requiring them to take approximately 90% of their energy from the grid. The baseline, however, is 64.52% self-sufficient, using more solar energy than grid energy. Since the baseline farm requires much more land to operate, there is more space and capacity to produce solar energy. The circular process energy intensity for the FF was larger than the baseline's (5.18 times greater). Without including processing energy use to make the systems more comparable, the indicator for FF was 3.7 times larger (0.027 kWh/kg/day). It is expected that the baseline would perform better with this indicator because they produce much more internally derived (solar) energy.

For the comparative indicators comparing the energy demand per liter of milk, the FF minimizes demand by 24.95% when processing usage is disregarded for the FF.

For a summary of the results presented see Table 4.3 below.

Table 4.3: Summary of results for ‘Using Renewable Energy’ circular action indicators

Circular Action: Using Renewable Energy		
Results: FF		
Indicator	*Result*	*Unit*
Electrical energy self sufficiency	9.36	%
Circular process energy intensity	0.044	kWh/kg/day
Results: Baseline		
Indicator	*Result*	*Unit*
Electrical energy self sufficiency	64.52	%
Circular process energy intensity	0.0085	kWh/kg/day
Results: Comparative Indicator		
Indicator	*Result*	*Unit*
Electrical energy demand minimization w/o processing energy	24.95	%

4.4.2. Water and Nutrient Recovery Indicators

For nutrient and water recovery, the indicators are quite simple and are not currently being compared to anything because the baseline has a very different approach to nutrient management. These results still indicate how FF is performing in terms of the proclaimed circular action. For both N and P, less than half of the input nutrients are recovered (41.28% and 38.23% respectively) this is easy to view on the Sankey diagrams knowing that the liquid fraction of the manure is all being lost. Water recovery is only 10.09% of the input which is also expected because the only water recovered is in the products, and there is a large amount of wastewater produced. The results are summarized in Table 4.4 below.

Table 4.4: Summary of results for ‘Water and Nutrient Recovery’ circular action indicators

Circular Action: Water and Nutrient Recovery		
Results: FF		
Indicator	*Result*	*Unit*
N recovery rate	41.28	%
P recovery rate	38.25	%
Water recovery in products	10.09	%

4.4.3. Waste Minimization Indicators

The waste index compares the mass of waste to the mass of total input. It was calculated to be 85%, meaning only 15% of the input mass is not wasted. This value is likely high because, even though some of the manure is saved, the mass of water wasted is so large compared to the manure saved that it does not have as significant an impact as the farm would expect. The waste utilization index compares the amount of waste utilized to the total waste. Again, due to the water and nutrient losses, this fraction is very small (3.1%). Table 4.5 summarizes the results for these indicators.

Table 4.5: Summary of results for ‘Waste Minimization’ circular action indicators

Circular Action: Waste Minimization		
Results: FF		
Indicator	*Result*	*Unit*
Waste index	85.20	%
Waste utilization index	3.10	%

4.4.4. Using a Non-Finite Water Source

This group of indicators is derived from the FF's claims that they use rainwater collection as a water source. Based on the indicators calculated, in reality, only 2.71% of their water use is from an internally derived renewable source (rainwater). They are using the roof as a collection area which is only $25m^2$ which does not give them a large capacity for rainwater collection. If the Rainmaker, a small-scale desalination system they are trying to implement, is included along with rainwater as an internally derived source, the self-sufficiency becomes 5.08%. The rainmaker does not make that large of a difference because it can only produce 450L/d (when it is operational). The baseline is assumed to have a 100% self-sufficiency because they obtain water from their own water source. This does not necessarily mean their source is non-finite, but there is a lack of data on their water use. Table 4.6 summarizes the results for this circular action.

Table 4.6: Summary of results for 'Using a Non-Finite Source of Water' circular action indicators

Circular Action: Using a Non-Finite Source of Water		
Results: FF		
Indicator	*Result*	*Unit*
% water self sufficiency	2.71	%

4.4.5. Eliminate Transport to a Processing Facility

Table 4.7 below describes the indicator results of the FF eliminating transport to a processing facility. Due to the FF's location in the city, their model focuses on reducing transport emissions. Based on CO_2 emissions, there was a reduction of 23.63% according to the comparison indicator. The small scale of the FF, the use of urban transport trucks, and the transport of waste likely explain why the reduction is not greater.

Table 4.7: Summary of results for 'Eliminate Transport to a Processing Facility' circular action indicators

Circular Action: Eliminate Transport to a Processing Facility		
Results: FF		
Indicator	*Result*	*Unit*
CO_2 emissions from transport	3.76	CO_2/ L milk
Results: Baseline		
Indicator	*Result*	*Unit*
CO_2 emissions from transport	4.93	CO_2/ L milk
Results: Comparative Indicator		
Indicator	*Result*	*Unit*
% reduced carbon emissions for transportation	23.63	%

4.4.6. Using Recycled Feed Crop

Several different indicators were calculated regarding the FF's feed. For the percentage of recycled feed, the FF is considered to use 100% recycled feed. This is because although all of it is grown elsewhere, none of it is grown specifically for animal feed and would otherwise be a waste product. In contrast, the baseline only uses bierbostel as a recycled ingredient, accounting for 4.94% of their feed; the rest is grown on the farm or imported. Using recycled feed also impacts the land use of the farm. Compared to the baseline, FF uses 99.11% less land per liter of milk. This is expected because FF does not grow any of its own feed, and its main operations are focused on water.

In terms of cost savings from using recycled feed, FF spends more money per liter of milk than the baseline. Although it is a waste product, FF still has to pay for its feed, and buying all the feed is mostly comparable to the price of growing it. This calculation also contains uncertainty and is largely estimated from literature.

Finally, feed efficiency measures how effectively recycled feed impacts milk production. For FF, feed efficiency was calculated to be 0.95. Table 4.8 below summarizes these findings.

Table 4.8: Summary of results for ‘Using Recycled Feed Crop’ circular action indicators

Circular Action: Using Recycled Feed Crop		
Results: FF		
Indicator	*Result*	*Unit*
% recycled feed	100	%
Land use	0.0025	ha/L milk
Feed cost	0.12	euro/L milk
Feed efficiency	0.95	kg milk/kg DW feed
Results: Baseline		
Indicator	*Result*	*Unit*
% recycled feed	4.94	%
Land use	0.03	ha/L milk
Feed cost	0.11	euro/L milk
Results: Comparative Indicator		
% reduction in land use	99.11	%
% reduction in feed cost	-7.84	%

4.5. System Testing

4.5.1. Sensitivity

While fine-tuning the nutrient balance, the amount of nitrogen and phosphorus in manure proved to be highly sensitive variables that needed to be adjusted to close the balance. Without adjusting the values from literature, the balances are off by 18% for N and 25% for P. Since such a large range from literature is used for determining energy use in milk processing, and ultimately this variable was used to close the balance, it was investigated how choosing an energy use at the upper and lower bound of the range would impact the energy balance. If an energy use of 1 kWh/ L milk is chosen the balance is off by 12% and if an energy use of 0.1 kWh/ L milk the balance is off by 26%. Table 4.9 below summarizes the results of this investigation.

Table 4.9: Variables tested for sensitivity

Sensitive Variables			
	Value used in analysis to close the balance	**Value reported in literature**	**Impact on balance if value from literature is used**
Nitrogen in Manure	4.20	3% [32]	Balance off by 18%
Phosphorus in Manure	1.53	2% [33]	Balance off by 25%
Energy used in milk processing	0.711 kWh/L milk	0-1 kWh/L milk	Balance off by 12-26%

Also investigated was the sensitivity of the feed composition. The % not balanced for the nutrient balance can now be compared for the chosen feed composition and a hypothetical composition including ‘treats’. Table 4.10 shows the impact on the nutrient balance from changing the feed composition.

Table 4.10: Sensitivity of feed composition and its impact on the nutrient balance

Feed Composition Sensitivity						
	N in feed (kg/day)	P in Feed (kg/day)	Balance N (kg N/day)	Balance P (kg P/day)	% Not Balanced N	% Not Balanced P
Used in Analysis (Grass, BSG, DDGS)	20	5.61	0.00099	-0.017	0.0050	0.30
Including 'treats' (Grass, BSG, DDGS, Orange Peels, Bread)	24.17	5.70	4.17	0.072	17.24	1.26

4.5.2. Seasonality

To give insight into the uncertainty of using an averaged value for solar production the seasonality was considered and Z scores show the number of standard deviations from the mean for each season. If the Z score is negative it means the amount is that many standard deviations below the mean while positive indicates it is above the mean. Table 4.11 shows the chosen months and Z scores for each.

Table 4.11: Seasonality for solar production and variance from the mean

Seasonality for Solar Production				
	Date Used	Amount	Unit	Z score
Winter Month	Dec-23	14.93	kWh/month	-1.64
Spring Month	Apr-24	154.46	kWh/month	0.015
Summer Month	Jul-23	203.50	kWh/month	0.60
Fall Month	Oct-23	60.96	kWh/month	-1.10
Mean used		153.20	kWh/month	
Standard Deviation		84.11	kWh/month	

4.5.3. Major Assumptions

To check the uncertainty of major assumptions for water use in milk processing values from literature and measured values were used to compare and validate the assumptions. Table 4.12 below compares the assumed values with values from literature or measured values.

Table 4.12: Verification of water use in milk processing

Water Use in Milk Processing				
	Used in Analysis	Unit	Literature Comparison/ Measured Value	Unit
Wash Water, Cooling Water (Glycol), Cheese Wash	4	L water/L milk	0.33-12.61 [41]	L water/L milk
Cooling Water OTC	13,000	L/day	10,385.99	L/day

4.5.4. Uncertainty in Indicators

Due to data availability, some indicators are more certain than others and data sources should be identified and discussed to make some indicators more certain in the future. The table 4.13 below lists the indicators with the most uncertainty, an explanation of why there is uncertainty, and how the uncertainty within such indicators can be improved.

Table 4.13: Largest uncertainties within indicators and data-related solutions to reduce uncertainty

Largest Indicator Uncertainties		
Indicator	*Explanation*	*Solutions*
CO2 emissions from transport	• Exact truck emissions were unknown, all assumed from literature for Baseline and FF. • Exact frequency unknown (based on weight of goods).	• Obtain fuel efficiencies from actual vehicles used.
Land use	• Does not consider the area on water, office or store, only grazing area. • Area for feed crop is all based on yields per hectare which is estimated from literature.	• Talk with the baseline to obtain more specific land use data. • Include total land used for the FF.
Feed Cost	• All costs are estimated from literature, some from other countries.	• Obtain data on how much is spent on feed for FF and Baseline.
N & P Recovery rates	• Screw press separation efficiency assumed from literature	• Measure N and P in liquid and solid fractions of manure to obtain the separation efficiencies.

4.6. Improvement Scenarios

4.6.1. Identification

Based on the gaps in circularity identified in the circularity analysis, four scenarios were identified to expand upon and offer as solutions to the gaps identified. Table 4.14 below explains the chosen scenarios and includes the principle behind them and their intended impacts.

Table 4.14: Summary of chosen scenarios and their intended impacts on indicators

Scenario	Principle	Intended circularity/indicator impact
Update cooling system	Switch OTC water source from the grid to from the river	Reduce water waste Increase self sufficiency
Add Desalination	Switch water source from the grid to river water	Increase self-sufficiency
Update current urine treatment system	Add P precipitation step and denitrification step	Increase water & nutrient recovery Decrease waste Increase self sufficiency
Redesign urine treatment system	Add an anaerobic digester to recover biogas	Increase self sufficiency Increase renewable energy use

For the four scenarios derived, feasibility and indicator results were identified. From these results recommendations for the FF can be made.

4.6.2. Update Cooling System

Water Quality Analysis and Risks

As a whole, the results of the water quality analysis show minimal scaling risks, and most parameters are within the standards for drinking water or are typical of surface water. The first parameters investigated include general water quality measures, which can be indicators of pollution and assess risks of corrosion. These include COD, BOD, TSS, TDS, and DO. The BOD concentration is low, indicating a low risk for biological fouling [55]. COD is typical for surface water, but its value may pose a risk of fouling [56]. TSS is also moderate, and suspended solids in the water can cause fouling [56]. The TDS and DO are helpful in assessing the risk of corrosion, and in this case, there is a risk [57], [58]. Since a risk of corrosion is plausible from these parameters, the Ryznar index

(RI) for both the FF and tap water confirms the risk. Based on the Rynzar index, the tap water currently being used is actually more aggressive and has a higher risk of corrosion than surface water. When comparing the ion concentrations to Dutch drinking water standards, only Na and K exceed the standards. Finally, the PHREEQC model only showed a positive SI (supersaturated) for Barite at 18°C. Common scalents such as calcite do not show a risk of precipitation (dissolved SI<0) at the river temperature or higher temperatures. This indicates there is a low scaling risk overall. Tables 4.15 and 4.16 summarize the most important results. See index C.2 for complete data sets.

Table 4.15: Nieuwe Maas Water Quality Parameters

Parameter	Amount	Unit	Implications for use in OTC
BOD w/ allylthioureum	1.18	mg/L	Minimal biodegradable organics, low risk of biofouling. <5 allowed for drinking water [55].
COD	11.6	mg/L	Typical for surface water (normal range is 5-20mg/L) [56]
TSS	23.35	mg/L	Water with TSS <20 is considered clear [56].
TDS	627	mg/L	Slightly brackish, freshwater <500mg/L [59].
Dissolved oxygen	10.4	mg/L	Higher DO can lead to corrosion (average 6.5-8mg/L) [57].
Ryznar index for FF	7.4		6.8<RI<8.5 Water is aggressive 7.5-9 Corrosion significant RI> 8.5 Water is very aggressive >9 Corrosion intolerable
Ryznar index for Tap	12		6.8<RI<8.5 Water is aggressive 7.5-9 Corrosion significant RI> 8.5 Water is very aggressive >9 Corrosion intolerable

Table 4.16: Summary of results of water quality analysis and PHREEQC model

Ions above Dutch drinking water standards		
Parameter	Nieuwe Maas Concentration (mg/L)	Dutch DW Standard (mg/L) [58]
Na	229.24	150
Saturation indices of phases with risk of scaling (from PHREEQC)		
Phase	SI	Temperature (◦C)
Barite	0.12	18
Barite	-0.02	30

Updated Indicators

Because the amount of wastewater would be impacted by using OTC from the river, the indicators waste index and waste utilization index were affected. Table 4.17 presents the results of the updated indicators when the river is used as a source for OTC for the compressor, along with a comparison to the base model.

For the circular action 'Waste Minimization', significant changes to the waste index and waste utilization index were observed. The waste index improved to 56%, meaning 56% of the inputs become waste, compared to 85% in the base model. Between the base model and the scenario, there is an absolute difference of 29 % and a percent difference of 34.24% for the waste index. The waste utilization index also improved significantly to 12% meaning 12% of inputs are now used to create products, compared to 3% in the base model. This results in an absolute difference of 9%, indicating a decrease of 284.79%.

For the circular action ‘Using a Non-Finite Water Source’, an improvement in water self-sufficiency was found. The percentage of water self-sufficiency in the cooling system scenario is 70.88%, compared to 2.71% in the base model. This results in an absolute difference of 68.18%, indicating an improvement of 2516.20%. This high percentage difference reflects a substantial increase in self-sufficiency, which helps to reduce reliance on external water sources.

Table 4.17: Results of updated indicators using the river as a source for OTC and potential improvement

Results: Updated Cooling System					
Circular action: Waste Minimization					
Indicator	*Cooling system scenario*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
Waste index	56	85	29	%	34.24%
Waste utilization index	12	3.1	9	%	284.79%
Circular action: Using a Non-Finite Water Source					
Indicator	*Cooling system scenario*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
% water self sufficiency	70.88	2.71	68.18	%	2516.20%

4.6.3. Add Desalination

WAVE Model

The most relevant results for the feasibility of this scenario are the energy use, permeate water quality, chemical use, and brine production. Based on the projection energy needed to produce 20m^3 water per day (current usage by the FF) is 2.5kWh/day or 135kWh/month. The permeate no longer contains too much sodium but will need remineralization to make tap water (see table 4.18 for a side-by-side comparison of the quality before NF, after NF, and tap water [60]). The projection does not include the chemicals needed to remineralize, but this is an added cost that should be considered. The report also indicates there is a scaling risk in the membrane without the addition of chemicals. With the chemicals added in the model (NaOH to increase pH and $Na_6P_6O_{18}$ as a scale inhibitor) the chemical cost is $0.7 per day or $255 per year. The concentrate produced is 0.45m^3/hour or 10,800 L/day and has a TDS 2,491 mg/L. Table 4.19 below summarizes these relevant parameters from the report.

Table 4.18: Influent and permeate quality for NF compared to current source

Parameter	Nieuwe Maas concentration (mg/L)	Nieuwe Maas concentration after NF (mg/L)	Evides tap water (current source) (mg/L) [60]
Ca	75.6	1.52	45
Mg	27.7	0.49	6.6
Na	180	32.59	29
K	9.41	1.65	5.4
NH_4	0.06	0.02	<0.05
Ba	0.06	0.01	0.014
Sr	0.5	0.05	0.13
CO3	0.133	0	
HCO3	172	4.74	120
SO4	93	1.04	40
Cl	62.4 (330.5 to balance)	51.66	41
F	0.14	0.03	0.14
NO3	2.6	1.26	11
PO4	0.06	0	
SiO2	2.94	0.28	
B	0.16	0.08	0.035

Table 4.19: Summary of most relevant parameters from WAVE report for full report see C.2.3

Figures from WAVE report		
Parameter	**Amount**	**Unit**
Energy use	2.5	kWh/day
Chemical cost	0.7	$
Concentrate production	10,800	L/day
Concentrate TDS	2,491	mg/L

Updated Indicators

Adding desalination impacts energy use and water use on the farm, affecting both the ‘Using Renewable Energy’ and ‘Using a Non-Finite Water Source’ indicators. Table 4.20 shows the updated indicators for this scenario compared to the base model.

As expected, both energy self-sufficiency and circular process energy intensity perform worse when NF desalination is implemented due to increased energy use. However, due to the small energy footprint of the methods chosen, the trade-off is minor. Self-sufficiency decreased to 8.64%, compared to 9.36% in the base model, with an absolute difference of 0.71% and a percent difference of 7.62%. Circular process energy intensity increased slightly to 0.05 kWh/kg/day from 0.04 kWh/kg/day, with an absolute difference of 0.0044 kWh/kg/day and a percent difference of 10.12

In this scenario, water self-sufficiency is assumed to be 100%, as mentioned in the methods, creating a significant increase in water self-sufficiency for the farm. Compared to the original model (2.71% self-sufficiency), an absolute difference of 97.21% and a percentage difference of 3590.63% were found. The percentage difference reflects a substantial increase in self-sufficiency, reducing the need for external water sources.

The self-sufficiency was also recalculated to include the Rainmaker machine’s current capacity. Rainmaker reports the maximum capacity to be 450L/day for an inlet low rate of 10 L/min. To meet the current demand of around 20,000 L/day the rainmaker would need to increase its capacity by 44 times. Based on Rainmaker's larger installations it is likely a larger system would require external energy. They have a system in Gran Canaria that uses wind and solar energy, but the FF currently may not have the capacity to increase solar production due to space concerns. This system may beget further investigation, but due to time constraints, desalination using NF was focused on in this study.

Table 4.20: Results of updated indicators from adding desalination and potential improvement

Results: Add desalination					
Circular action: Using Renewable Energy					
Indicator	*Desalination scenario*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
Electrical Energy self sufficiency	8.64	9.36	0.71	%	7.62%
Circular process energy intensity	0.05	0.04	0.0044	kWh/kg/day	10.12%
Circular action: Using a Non-Finite Water Source					
Indicator	*Desalination scenario*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
% water self-sufficiency (NF)	100	2.71	97.29	%	3590.63%
% water self-sufficiency (Rainmaker)	5.08	2.71	2.30	%	87.45

4.6.4. Update Current Urine Treatment System

Literature Investigation

To best decide on the course of action for the FF to better manage the liquid fraction of manure, several papers discussing biological sewage treatment technology and manure management were studied. For phosphorus, Hjorth, Christensen, Christensen, *et al.* [61] offers important insights on separation technologies, separation efficiencies, and improvements. Pretreatment of slurry by adding multivalent ions to precipitate phosphorus was mentioned by both Hjorth, Christensen, Christensen, *et al.* [61] and Lyons, Cathcart, Frost, *et al.* [62], and was then identified as the most reasonable scenario for the FF to increase P separation efficiency in the solid fraction of manure. Aluminum sulfate and ferric chloride were proven to be the most efficient for this task [61]. This step will change the pH and may increase or decrease NH3 emissions, which should be considered. In a scenario most similar to the FF, which used cattle slurry and pressurized filtration (screw press) separation method, an efficiency of 78% P in the solid fraction was achieved with the addition of CaO. This efficiency was used for the indicator calculations.

Managing N is more challenging if the goal is to increase the amount of N in the solid fraction. N is much more soluble than P, and even without any pretreatment, the separation efficiency for P is much higher than for N [51]. With chemical additions, there is a small impact on N retention in the solid fraction, but it is likely that >50% will remain in the liquid fraction of manure [61]. Another solution is to reconfigure the existing biological treatment for N and add a denitrification step. In this scenario, the N is still technically 'wasted' as N_2 gas, but this allows the nitrogen cycle to restart with nitrogen fixation. This process removes bioavailable nitrogen from the system but could prevent harmful environmental impacts such as leaching and provide reusable water for the farm [63].

Traditional denitrification occurs via heterotrophic denitrifying bacteria, which transform nitrate into nitrogen gas using organic matter as an electron donor. Anoxic conditions, nitrate, and an available carbon source are required for denitrification to occur. Many configurations are commonly used in biological wastewater treatment. Pre-denitrification is a configuration where denitrification occurs before the nitrification process. The main advantage of pre-denitrification is that there is no need to add an external carbon source because there is carbon present in the influent slurry that can be used by the bacteria. The issue is nitrate availability. Since nitrification has not yet occurred, there is not enough nitrate present for efficient removal. A recycle stream from a later tank can be a solution to this problem but requires optimization. Post-denitrification occurs after nitrification and is not often used on a large scale because an external carbon source is required, which can be expensive. However, it requires less process control and has high removal rates due to the availability of nitrate. Both configurations can achieve removal rates up to 99% if optimized and operated correctly [64].

Anammox bacteria were also investigated, which can directly convert ammonium and nitrite into nitrogen gas. This process requires less oxygen and no external carbon source, but it requires operational expertise and tends to have lower removal efficiencies (60-80%) [Water Mining WP5 (confidential)].

For the FF, a conservative removal efficiency of 75% was assumed based on the literature for calculated indicators. Considering the current treatment system of the FF, the post-denitrification configuration appears to be the easiest to implement and requires the least amount of operational expertise. However, more research should be focused on this area in the future. Building a successful system requires proper experimentation and testing of the influent. This result should be viewed more as an exploration of possibilities and background for the chosen efficiencies used for the indicator calculations.

Updated Indicators

Table 4.21 below presents the results of the updated indicators after implementing improvements to the urine treatment system. The three circular actions that would be impacted are Water and Nutrient Recovery, Waste Minimization, and Using a Non-Finite Water Source.

For 'Water and Nutrient Recovery', the P recovery rate and water recovery in products indicators would be impacted. The phosphorus recovery rate increased significantly from 38.2% in the base model to 81.07% in the updated scenario, representing an absolute difference of 42.82% and a percentage improvement of 111.95%. This indicates more than doubling of phosphorus recovery efficiency. Water recovery saw an improvement from 10.09% to 16.50%, with an absolute difference of 6.40% and a percentage improvement of 63.45%. This improvement indicates enhanced efficiency in reclaiming water from urine.

For 'Waste Minimization', both the Waste Index and Waste Utilization Index would be impacted due to an increase in nitrogen waste and a decrease in phosphorus and water waste. The waste index slightly decreased from 0.85 kg/kg to 0.78 kg/kg, indicating a minor reduction in waste generation. The absolute difference of 0.07 kg/kg and a percentage improvement of 8.27% indicate a small improvement in waste management. The waste utilization index improved from 0.03 kg/kg to 0.10 kg/kg, indicating a significant impact on waste utilization practices. The absolute difference of 0.07 kg/kg and a percentage improvement of 230.90% highlight a substantial increase in using waste as a resource.

For 'Using a Non-Finite Water Source', the water self-sufficiency indicator is impacted because water is made available for reuse after treatment. The water self-sufficiency indicator showed improvement from 2.71% in the base model to 9.18% in the updated scenario. The absolute difference of 6.47% and a percentage improvement of 238.93% show significant potential for improvement.

Table 4.21: Results of updated indicators if the urine treatment system is updated and potential for improvement

Results: Update Urine Treatment System					
Circular action: Water and Nutrient Recovery					
Indicator	*Scenario implemented*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
P recovery rate	81.07	38.25	42.82	%	111.95
Water recovery in products	16.50	10.09	6.40	%	63.45
Circular action: Waste Minimization					
Indicator	*Scenario implemented*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
Waste index	0.78	0.85	0.07	kg/kg	8.27
Waste utilization index	0.10	0.03	0.07	kg/kg	230.90
Circular action: Using a Non-Finite Water Source					
Indicator	*Scenario implemented*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
% water self sufficiency	9.18	2.71	6.47	%	238.93

Connecting Urine Treatment System to Vertical Farm

To further increase circularity, the possibility of using the resulting water and nutrients from urine treatment as a water and nutrient source for the vertical farm was investigated. The main factor investigated was how large the vertical farm would need to be to use all of the water and nutrients and how that size compares to the current size. With the water need assumption or micro greens from the methods, the farm size would need to be 506.24 m^2 leading to a factor of increase in size of 3.62 times.

4.6.5. Redesign Urine Treatment System

The final scenario involves completely redesigning the urine treatment system to include anaerobic treatment of the manure slurry as a pre-treatment step. Results from literature regarding the pros and cons of using the technology for the FF are presented in the table 4.22 below.

The benefits of adding AD are numerous and may significantly increase the circularity of the FF in terms of energy (quantification in indicator results). The biggest concern for the feasibility that has come from this literature search is the operational complexity and capital costs. Since the FF is a small scale operation and does not currently have much expertise in terms of water treatment, a successful AD may be difficult to configure at this stage in the farm's development. Shelford [65] did a cost analysis for the economic advantages of AD and found that even for 30 cows there was some net profit. It could be economically viable at this scale but would require expertise to ensure it works efficiently to make a profit.

Table 4.22: Pros and cons of adding AD to the FF

Pros	FF Implications	Source
Production of biogas	Increase energy self-sufficiency Increase use of renewable energy	Aguirre-Villegas, Larson, and Sharara [51]
Further GHG reduction when coupled with SLS	Reduce overall farm footprint	Aguirre-Villegas, Larson, and Sharara [51]
Reduction in sludge compared to aerobic treatment	Reduce waste from sludge	Ma, Guo, Qin, *et al.* [66]
Reduction in TS, VS, COD	Simplified further treatment	Aguirre-Villegas, Larson, and Sharara [51]
Increase in TAN	Increases separation efficiency for SLS	Aguirre-Villegas, Larson, and Sharara [51]
Odor reduction	Important for a farm within the city	*Emissions Control Strategies for Manure Storage Facilities* [67]
Cons	**FF Implications**	**Source**
High capital costs	Might not be an option at this scale	Aguirre-Villegas, Larson, and Sharara [51]
High operating temperatures	Difficult for Dutch climate	*Emissions Control Strategies for Manure Storage Facilities* [67]
High chance of failure	Requires knowledge and expertise	*Emissions Control Strategies for Manure Storage Facilities* [67]
Additional treatment necessary	SLS and nutrient removal would still be needed	*Emissions Control Strategies for Manure Storage Facilities* [67]

Updated Indicators

The redesign of the urine treatment system yields significant changes in key indicators, as shown in Table 4.23. Assuming the rates of conversion and the mass of manure given in the methods adding AD for the FF would produce 4 times more energy than is currently used on the farm and in turn make the FF 406.86% energy self-sufficient. This is a stark increase from the base model of 9.26%. The circular process energy intensity becomes 0 because all of the energy is internally sourced.

Table 4.23: Results of updated indicators if the urine treatment system is redesigned and potential for improvement

Results: Redesign Urine Treatment System					
Circular action: Using Renewable Energy					
Indicator	*Scenario implemented*	*Base model*	*Absolute difference*	*Unit*	*% Difference*
Electrical Energy self sufficiency	406.86	9.36	397.50	%	4248.54%
Circular process energy intensity	0.00	0.044	0.044	kWh/kg/day	100.00%

5
Discussion

5.1. Water Management

5.1.1. Water Balance

The first result relating to water management on the FF is the calculated water balance. This balance estimated the distribution of flows through different processes and helped to identify gaps in circularity by quantifying losses. The water use for milk production is comparable to the baseline when estimated per L of milk. Based on this balance, FF uses 4.31 L water/L milk and the baseline uses 2.77 L water/L milk. The FF used much more water than expected overall due to using OTC for a compressor within the cooling system of milk processing. In the Best Available Techniques document for European dairies, water use for milk processing was 0.33-12.61 L water/L milk as opposed to the FF's 22.09 L water/L milk [41]. Meaning the FF used 66.94-1.75% more water per L milk in milk processing than the average European dairy. This served as compelling evidence for identifying a circularity gap in this area. Not only is the FF using a considerable amount of water to likely cool a single compressor, but they are also wasting water that is very clean and has huge potential to be used again. This is both wasteful and expensive for the farm because they must pay for the water itself, and the taxes for wastewater treatment.

Also evident from the water balance is how little rainwater is being used and how the FF is entirely dependent on the city system. Because they are in the city, there is not a lot of space for rainwater collection and they do not have their own source of water like Veelon. They are, however, on the Nieuwe Meuse River, but are not currently using any water from the river.

5.1.2. Water Related Indicators

Several indicators quantify important metrics regarding the circularity of the FF's water systems. Within the circular action 'Water and Nutrient Recovery', the 'Water recovery in products' indicator quantified the % water recovered compared to the input. The low recovery of 10.09% highlights the need for water saving and recovery initiatives, and reflects the losses seen in the water balance. The performance of the waste index and waste utilization index indicators of the 'Waste Minimization' circular action are also reflective of the high amount of water used and wasted, performing poorly due the the high amount of water that is wasted. The final indicator is for the circular action 'Using a Non-Finite Source of Water' and calculated the water self-sufficiency. This indicator also performed poorly with a self-sufficiency of 2.71%. This reflects the small amount of rainwater used compared to the water from the grid.

The indicators for water performed poorly as a whole when trying to verify circularity claims. The circular actions implemented for water management have little impact due to the water in the cooling system which severely increases usage and waste for the whole farm.

There is also a significant amount of uncertainty within both the water balance and indicators. This is because there are very few measurements of water usage on the farm and most data came from word of mouth and literature. In the future, the farm should install flow meters in areas such as the milk processing center to have a better idea of usage and losses. This would help with the accuracy of the indicators used and allow for more concrete conclusions.

5.2. Electrical Energy Usage

5.2.1. Energy Balance

To first quantify energy use and losses at the farm, the energy use for major processes was calculated. Accurately determining the usages at at process level was difficult due to a lack of data. Specifically, the water usage for processing is highly uncertain because equipment ratings were not available, and estimates were used to close the balance. The Sankey diagram was process level, but energy indicators only consider total demand which is a known value. Production demand (w/o processing) and the estimated demand are both within range with the baseline for production or the BAT document for processing which helps to verify assumptions made. Since both energy for production and processing have a comparable metric and no large losses were identified it can be assumed the FF is efficiently using its energy. Still, more electricity measures within the farm would be useful to further optimize usage and establish a more accurate analysis.

5.2.2. Energy Indicators

Even if energy use was found to be reasonable for the farm, the indicator calculations help to ascertain whether or not energy use on the FF is circular. The only indicators that consider energy use is the ‘Using Renewable Energy’ indicator set. Similarly to the water circular actions, the FF’s claim that they are energy self-sufficient due to the use of solar energy is a vast overestimation. They do have solar panels installed, but the solar energy accounts for less than 10% of on-farm usage, and they perform far worse than the baseline farm for energy self-sufficiency. Similarly, they do not perform well for the circular process energy intensity since most of their energy is from the grid (only 40% renewable). For the comparative indicator (which should be taken lightly due to the large differences in models between the FF and the baseline) the FF does have a lower demand than the baseline when processing energy is removed. Based on this comparison it is useful to know that the FF’s technical advancements such as cleaning robots and manure separation do not use more energy per L milk than the baseline. This aligns with the energy efficiency claims of these devices, which was a significant selling point during their research and procurement.

From the energy use investigation, it is clear that the farm is not using an excessive amount of energy compared to other farms, but the source of energy and self-sufficiency could be improved to increase circularity. Adding more solar panels would be the most straightforward solution, but because of the FF’s model within the city, space to place the panels is a concern. The current panels are on water, but in their current location, there is not much room for more.

Addressing these challenges will be crucial for the FF to improve its energy circularity and better align with its circularity claims. Exploring alternative solutions, such as vertical solar panels or community solar projects, could be viable options to overcome space limitations and increase renewable energy usage.

5.3. Waste Management

5.3.1. Nutrient balance

To first understand and quantify nutrient losses within waste management a nutrient balance was calculated. Useful feed data made it possible to understand feed composition and estimate N and P in the feed to serve as an input. Because nutrient losses are a large concern for farm circularity, there was significant supporting literature for nutrient balances, screw press separation efficiency, and separation efficiency improvement that made this balance possible [34], [51], [62]. The nutrient separation efficiencies of the screw press separator were obtained from literature, and it is important to note that efficiencies vary depending on the farm. The liquid and solid fractions should be tested for N and P to determine the exact efficiency. It is expected that little N would be present in the solid fraction because it is very soluble. P is less soluble, but in Aguirre-Villegas, Larson, and Sharara [51] the screw press separation has the lowest efficiency for P of separation techniques and helped to verify the distribution chosen (29% in solid fraction 71% in liquid fraction).

Regarding circularity gaps, the N and P balances highlight the large loss of nutrients from disposing the liquid fraction of manure in the sewer after treatment. For N, some NH_3 losses are inevitable, but a reduction in losses may be possible by adding covers to dried manure. Aguirre-Villegas, Besson, and Larson [34] mentions that due to a higher pH for solid manure, NH_3 volatilization is prominent, but covers can reduce the emissions by limiting contact with the wind. Currently, manure is being stored in open-air bags awaiting pickup. The losses from whey are almost negligible in regards to the whole system, likely because only around 10% of milk produced is used for cheese. If production was scaled up with the same processing procedure, this loss may become more prominent.

5.3.2. Waste Management Indicators

The indicator sets 'Water and Nutrient Recovery', and 'Waste Minimization', most directly concern waste management. The N and P recovery rate indicators performed better than the water recovery, but <50% of both nutrients were recovered primarily because of the losses in the liquid fraction. Like other circular actions, effort is being made to be circular, but there is a need for optimization to increase efficiencies and prevent negative environmental impacts such as leaching. Typical farms using similar technologies have higher recovery rates primarily because they often utilize both liquid and solid fractions directly in the fields [67]. The baseline farm does not use separation but likely has much higher efficiencies for nutrient recovery rates because the entire slurry is used in the fields. The FF's whole model does not easily allow for slurry spreading and requires transport to do so. The 'Waste Minimization Indicators' (waste index and waste utilization index) also perform poorly but primarily because of the water waste as discussed in section 5.1.2. The low N and P recovery rates and water lost in the liquid fraction of manure do not help these indicators, but the wastewater in milk processing causes the largest issue. The disproportionate water losses make it harder to see/ understand the impact of waste minimization because of actions of using manure as a product because all wastes are considered not just the wastes from milk production. In the future, it may be interesting to investigate this indicator set without the processing waste to better understand the impact of the circular action.

5.4. Miscellaneous Indicators

The indicator sets for the circular actions 'Eliminate Transport to a Processing Facility' and 'Using Recycled Feed Crop' less directly fit into the categories of water, energy, and waste, but still hold interesting insight into the farm's circularity performance. The indicator for 'Eliminate Transport to a Processing Facility' focuses on CO_2 emissions from transport. While the FF does show a slight decrease in emissions compared to the baseline, the model for the FF does not drastically reduce emissions per L of milk produced. This is likely due to the trade-off between transporting milk for processing and transporting waste. On typical farms such as the baseline the produced waste is spread on the fields that produce feed crops. Because the FF does not grow feed crops and is in a city the waste must be exported. When comparing the model of the baseline, 100% of the feed is also imported instead of grown on-site. Also differing between the farms is the methods of transport used. The FF uses electric vehicles for small loads but still uses urban trucks for most feed imports. The baseline is assumed to use long haul trucks for its imports and exports which release less CO_2 than urban trucks. There were many assumptions from literature made for this calculation, but it is still interesting to see that the FF's intentions for reducing transport may not have the largest payoff because of the trade-offs within the model of their design. Positively the FF did reduce emissions by 23% and is taking a step in the right direction.

Finally, the indicators for 'Using Recycled Feed Crop' had varying performance depending on the indicator. The land use indicator performed very well as expected due to the FF's model of not growing feed crops and having the majority of its operations on water. With this decreased land use, a clear loss of self-sufficiency is evident in terms of feed and electricity. A large reason why the farm does not use more solar is because there is not much room for it in the current design of the farm.

The feed cost per L milk may be a trade-off of this model considering the recycled feed was found to be slightly more expensive than the baseline. Unfortunately, there was no cost reduction, but it is interesting to know that in terms of cost, this feed model is comparable to the baseline because there is only a slight difference in cost. The feed efficiency calculated was a bit lower than typical farms. Typically feed efficiency is between 1.3-2kg milk/kg DW feed [68]. This is expected because the FF does not center its model on only optimizing milk production and MRIJ cows produce less than other dairy breeds. The % recycled feed is considered to be 100% because no feed used was grown for the purpose of being animal feed. On the surface, this seems like a very circular model as opposed to the baseline's <5% recycled feed. It should be noted that the model relies on a linear system and may not be sustainable as the NL continues to adopt circular models. There are other trade-offs for using recycled feed and having a low land use already mentioned such as needing waste exports which increases transportation emissions.

The FF's very low land use for its level of productivity is something that makes its farming model truly unique. In future works, it would be interesting to calculate indicators and mass balances normalized by land used and compare to a typical farm. It is suspected the FF would operate more like an industrial facility instead of a farm with very high energy, water, and nutrient use per hectare. This indicates the FF is using its little land efficiently, but one should also consider the impacts on the land and the welfare of the animals. It is also important to consider the scalability of a process that even with its many innovations may stretch the ecosystems to their limit.

An analysis focused more on sustainability impacts such as global warming potential, acidification potential, eutrophication potential, and terrestrial ecotoxicity should be investigated using an LCA. Currently, the data is not available to do such analysis easily.

5.5. System Testing

5.5.1. Sensitivity

The variables investigated for sensitivity were all variables used to close the balance based on literature. The amount of N and P in manure was specifically chosen because while trying to close the balance it was noticed that even a slight change in these variables made a large difference in the balance. In the sensitivity analysis, the sensitivity of the variables can be seen by using the exact values from literature as opposed to the adjusted values and observing the change in the nutrient balance. The difference between the adjusted values and literature was small but caused the balance to be off by 18% for N and 25% for P validating the idea that these variables are sensitive. They are likely sensitive because the amount of nutrients in manure is multiplied by the mass of manure which is a large number and makes up a big portion of the balance.

The third variable tested for sensitivity was the energy assumed in milk processing. This value was also used to close the balance and may be slightly different in real life making its sensitivity relevant. Using the upper and lower limits of the range from literature revealed a balance off by 12-16%. The range, however, is quite large, and large changes would undoubtedly change the model. When adjusting the value only slightly, there was little impact on the energy balance indicating this variable is not very sensitive.

5.5.2. Seasonality

Although seeing the full impacts of seasonality on energy use was not possible because of the lack of monthly data for usage from Evides, the impacts of seasonality on solar production can be observed. As expected there is less production in the fall and winter months and the highest variance from the mean. All Z scores are less than 2 standard deviations from the mean indicating there is no severe outlier. It is expected there would be higher usage from Evides in winter months due to less solar production, and higher heating needs. The entire network usage (including office and store) from the months of May, August, and December 2023 were available and, though not entirely representative, the network usage for December was highest by around 200kWh which aligns with this theory. It is inevitable that the energy usage and production would vary by month and it is likely use the mean for solar production is an overestimate for several months, but for the sake of a general energy balance, the seasonal uncertainty is considered acceptable. In future analyses, more detailed data may allow for energy balances specific to the season and the identification of any seasonal losses.

5.5.3. Assumptions for Water Use in Milk Processing

To determine water use in milk processing estimations from operators were used and there was a very large mismatch between their estimation and the actual usage from Evides. It was then discovered that there was a compressor using once-through cooling and the gap was assumed to be from the compressor. To verify the order of magnitude, a small experiment was conducted to estimate the flow rate, but it was not very certain. After arsing concern over this gap, a flow meter was installed which can be used to verify the assumption. The flow meter averaged 10,385 L /day at the time this thesis was completed which is near the estimated 13,000 L/ day. This verifies the assumption and concretely identifies a large gap in circularity. The assumption was not perfectly accurate and was overestimated by around 3000L/ day. This indicates there is an underestimation somewhere in the balance. Since most of this balance is made up of values estimated by the FF or literature it is logical that there is uncertainty. The most uncertain areas where an underestimation may have been made are for pressure washing, cleaning water, or water for glycol cooling. Despite uncertainties, the water balance and the indicators that came from it allowed for major gaps in circularity to be identified and have already helped raise concerns over water usage with FF staff.

To help distribute water use in milk processing other usages such as wash water, glycol cooling water, and cheese wash were also considered and compared with literature. Without considering the water use for the compressor, the water use per L milk is near the median of the standard water usage for milk processing in Europe. This is logical because these usages are relatively standard in the industry.

To reduce uncertainties and assumptions for water use in milk processing specifically, it is recommended that additional flow meters are installed specifically at the tap used for cleaning water. To increase the accuracy of the whole water balance it may be useful to install flow meters in the milk production part of the farm, especially for pressure washing. The FF's partnership with Montreal Solutions should make it easy to make the data easily available once the sensors are installed. The installation of the flow meter at the compressor is already a great step in the right direction.

5.5.4. Uncertainty in Indicators

The final part of system testing was to identify large uncertainties within the calculated indicators. All of the uncertainties identified are due to data that was missing or difficult to obtain so it was estimated from literature. The estimated data can give an idea about where the FF is at and it is not irrelevant, but a more accurate analysis could be completed with more specific data available. Some data, such as the separation efficiency of the manure separator, is not known by the farm and requires measurements. Other data, such as truck efficiencies and feed costs, can likely be determined with research. Many assumptions were made regarding the baseline farm and, in the future, more recent data collected for this thesis instead of a previous thesis may have helped to collect more specific data and made the baseline more useful.

5.6. Improvement Scenarios

5.6.1. Using River Water for OTC

The first water use improvement scenario aims to specifically fix the usage within the cooling system. The feasibility analysis focusing on the water quality risks revealed minimal scaling risk, but a risk of corrosion is evident. This risk, however, is higher with the current tap water being used, according to the Ryznar index. This is expected because tap water is normally slightly acidic and is often softened so lacks the protective minerals that can cause scaling and protect the pipe. Since the FF is currently using tap water for cooling, the compressor currently has a higher risk of corrosion than the river water, so corrosion would not be a large concern for the river water. Since the processing center operates with a batch process, there should be ample opportunities for necessary cleaning of the system to prevent both scaling and corrosion without chemical additives. In typical OTC systems, such as those used in power plants, further treatment may be necessary because the continuous process does not allow for regular system cleaning. For the FF it is feasible to use the Nieuwe Maas with limited to no pre-treatment.

To evaluate the potential impact of this scenario the 'Waste Minimization' and 'Using a Non-finite Water Source' indicator sets were recalculated. For both sets significant improvements were seen. The improvements in the waste indicators highlight the importance of wastewater on overall waste as both the waste index and waste utilization index were significantly improved without the losses from cooling. Most impacted was the self-sufficiency which is expected due to the large proportion of water that would no longer come from the grid in this scenario. With this scenario in place, the FF's water use in processing (assuming the river water is not 'used' because it is returned to the source in a similar condition) is within the range of other European processing centers according to the BAT document (0.33-12.61 L water/ L milk) with 3.89 L water/ L milk. Based upon both the water quality analysis and potential indicator improvement, this scenario is worth investigating further in the future as a solution for the OTC losses.

5.6.2. Adding Desalination

This scenario primarily focuses on increasing the farm's self-sufficiency by lessening its reliance on water from Evides. To assess feasibility, a projection model in WAVE was created. The projection revealed that an NF membrane is sufficient for removing hardness and salts with a low energy requirement. For operation, some chemicals are likely needed to increase pH and prevent scaling of membranes. Some remineralization is also necessary to make tap water. These chemical additions and the resulting brine are the largest obstacles to the feasibility of this scenario. Permits for both extraction and brine discharge would be necessary for this scenario to be possible. Further water testing would be beneficial, and this preliminary investigation would require significant testing and further consultation before implementation.

Both 'Using Renewable Energy' and 'Using a Non-Finite Water Source' were recalculated considering the WAVE projection. Assuming an increased energy usage for NF would increase the energy usage from the grid, a small decrease in self-sufficiency was calculated. Similarly, the circular process energy intensity increased slightly due to the increased usage from the grid. Overall, the energy usage would increase, but the energy trade-off is not detrimental to the feasibility of this solution (overall usage increases by 8.24%). The positive of adding an NF system is that the water self-sufficiency could reach 100% and remove the FF's reliance on the city water system.

The increase in water self-sufficiency is significantly larger than the trade-off decrease in energy self-sufficiency which helps to justify the increased energy use.

As mentioned in the WAVE report (C.2.3), the steps required to maintain the membranes, produce tap water, and brine management require more investigation and are seen as a larger hindrance to the feasibility of this scenario than the energy trade-off. Given that the biggest water-related gap is centered around the OTC in processing, it is logical to address that gap first. As explained in the first scenario, this is an easier fix, particularly for the current version of the farm. As the FF initiative and company grow and version two of the farm is realized, desalination using NF may be a plausible solution to utilize the water nearest the farm and become more self-sufficient.

5.6.3. Updating the Urine Treatment System

The scenario for updating the urine treatment system focuses directly on waste management. The literature investigation for the most feasible solution to increase the recovery of water, N, and P from the liquid fraction of manure explained the effects of adding chemicals before separation to increase the recovery of P in the solid fraction and discussed denitrification techniques to convert nitrate to nitrogen gas and recover the water. The P precipitation step is well covered in literature and would require little operational expertise making it a feasible solution for the FF. Denitrification is more complicated and requires operational knowledge and testing. Post-denitrification would be the easiest to add to the existing system, but an external source of COD is required which could be expensive. A possible option could be to use some of the solid fraction of manure as a source, but further studies would be needed to investigate this.

The updated indicators show the potential of higher P recovery and water recovery which also impacts the waste indicators and water self-sufficiency. It is important to note that the N recovery is not increased because N is lost as nitrogen gas. It is important to remove the nitrogen so that the resulting water is more usable and is not wasted. With a precipitation step around 80% of P can be recovered in the solid fraction. The water self-sufficiency increased to 9.18% which is not a huge improvement, but coupled with the updated OTC system this indicator has the potential to improve greatly. This system has the potential to make the manure processing system less wasteful, but cannot achieve full recovery due to sludge production, ammonia emissions, and removal efficiencies.

5.6.4. Connecting the Urine Treatment to the Vertical Farm

The results of connecting the treated water from urine treatment and the vertical farm estimate that the vertical farm must be scaled up by 3.62 times to use all the water from urine treatment. Since the system size used is the system that is currently under construction, it is not reasonable right now to increase the size. It is also unlikely a larger system would fit in the current space used for vertical farming. With the current system 22% of the treated water could be used for the farm and if it has had the nutrients removed, it has other uses such as for cleaning water or water for the robots in milk production. This calculation and idea of connecting the two systems should be kept in mind for future versions of the farm.

5.6.5. Redesigning the Urine Treatment System

The improvement scenario for redesigning the urine treatment system most directly impacts energy use. In terms of energy, installing an AD could be a great way to increase circularity for energy usage. Based on the conversions from weight of slurry to biogas, the amount of slurry produced per day could produce over four times the needed electricity for the farm. This also increases waste utilization and an energy product that can be monetized could be added to the farm's business model. However, as mentioned in the results, the feasibility of this solution at this time is a concern. A main concern is operational expertise. The current urine treatment is not a complicated operation but is currently not running due to clogging and lack of measurements to ensure proper treatment (operational concerns). For AD to be profitable at this scale it would need to be optimized and the farm would need someone who can ensure it is properly operated. Installing an AD and changing the setup of the urine treatment system would also require significant capital costs which may not be an option for the farm at this scale. Missouri Extention [69] estimates installation of an AD can cost anywhere from $400,000 to $5 million dollars. Shelford [65] found profitability at a scale as small as the FF, but from Missouri Extention [69] indicators of economic feasibility, the FF does not seem like a candidate because the operation does not have an energy bill of > $5000 per month. Economic costs were not a large part of this report, but in terms of installing an AD for the farm at this scale, they seem too important not to include. An AD has many benefits that may beget further investigation, but this investigation may be better suited for when the FF grows in scale.

5.6.6. Comparing Scenarios

After assessing the feasibility and indicator impacts for each of the scenarios comparisons can be made to determine scenarios that should take priority for further investigation. Also important to consider is the importance of the problem/ circularity gap that is being solved by the scenario. For example, the circularity gap and losses of water are significantly larger than nutrient or energy needs and should be assessed first.

The scenario that should take precedence is solving the OTC losses in milk processing. This scenario has a very large impact on indicators and has the simplest solution. The operational expertise needed is also minimal which is an important consideration for the farm due to its current scale and staff size. Also feasible is the pre-treatment of slurry to increase the separation efficiency of P. Denitrification to recover the water from the liquid fraction of manure also has several pros, but needs significantly more research and testing to better conclude its feasibility. If the water is successfully treated connecting the urine treatment to the vertical farm is plausible as a source to use some of the water, but it is not large enough in the current version of the farm to use the water only for vertical farming.

The final two scenarios are less feasible for the current version of the FF but may be useful recommendations for the future of the organization. Using NF to desalinate had less of an energy trade-off than expected, but brine management, chemical use, and remineralization steps make the solution less feasible, especially at the current scale. Finally, adding AD to manure management has massive potential for renewable energy generation, but requires significant expertise and capital costs that may outweigh its benefits in a farm this small.

5.7. Circularity vs Sustainability

After concluding the circularity assessment of the FF it is important to look back on the definitions of circularity and sustainability and discuss the implications for the FF. The definition used in this report for CE is “a sustainable economic system where economic growth is decoupled from resources use, through the reduction and re-circulation of natural resources.[11]”. In many ways, the FF fails to meet this definition and is not considered a circular economy despite its efforts. Most notably, looking at the indicators which refer to waste, the FF performs poorly indicating little reuse and reduction of natural resources. Its reliance on significant amounts of water and electricity from the grid indicates that the FF is still primarily operating as a linear economy. Additionally, their feed model may be recycled but still relies on the excess of a linear system which may become unreliable in the future.

In terms of sustainability, the definition used is “the balanced and systemic integration of intra and inter-generational economic, social, and environmental performance.” One might argue that the FF hits more of the points of sustainability than CE. Their environmental performance may not be optimized at this phase in its development, as demonstrated by the mass balances and indicators, but socially the FF works to promote circular farming and bring awareness to the environmental impacts of traditional farming. They frequently host guests to educate them on their mission which undoubtedly promotes sustainable initiatives to the general public. Economically, the FF uses the ideas of circularity to market their products which in turn might also be spreading a message of sustainability. This, however, is also problematic because based on this assessment the FF may be unknowingly exaggerating claims. Most of the self-proclaimed circular actions did not perform well in this assessment and the FF’s claims may need to be updated to reflect the reality of their performance to prevent greenwashing. It is the ethical responsibility of the farm to highlight its efforts toward a circular system while still admitting the difficulties of achieving circularity instead of making exaggerated claims.

While reflecting on the importance of understanding the difference between the concepts of CE and sustainability the FF serves as examples of the three relationships identified by Geissdoerfer, Savaget, Bocken, *et al.* [8]. Many of the FF’s circularity initiatives make the farm more sustainable and serve as a condition of sustainability and also beneficial for sustainability (conditional or beneficial relationship). Examples include circularity education initiatives or the valorization of manure. However, trade-off relationships can also be found such as using recycled feed which can be seen as a more sustainable feed model, but may not be circular due to the lack of self-sufficiency and reliance on a linear system.

5.8. Circularity Assessment Method

An interest in this thesis was the implementation of an indicator-based circularity assessment developed by Water Mining and whether it could be adapted to the context of the FF. Based upon the results and recommendations that can be drawn from the completed assessment, the method gives a clear picture of the FF based on indicators derived from its self-proclaimed circular actions. Through both mass and energy balances and the indicator calculation, gaps in circularity were easily identified. The same indicators were also helpful in quantifying the impact of the improvement scenarios. In literature, weaknesses of indicator-based assessments have highlighted data availability limitations [24]. This analysis was consistent with those claims as the largest difficulty throughout the project was a lack of data leading to many assumptions and using literature. Another concern is that indicator-based circularity analyses are not standardized [22], [23]. Although some standard indicators may be nice for comparisons, the specificity of the chosen indicators made for an interesting and detailed analysis. If the indicators were very broad they would likely have been less conclusive. The Water Mining method of deriving the indicators from circular actions worked well in this context.

6

Recommendations

6.1. Monitoring Systems

Additional monitoring systems are recommended to better understand system losses and more accurately perform circularity analyses. The FF is currently working with Montreal Solutions to install sensors and monitoring systems throughout the farm and connect to their platform, but gaps remain to be addressed. For water management, a flow meter connected to the tap used for cleaning would help to accurately quantify usage and help encourage water reuse. Another estimated flow is the water used for pressure washing. A flow meter attached to the pressure washing tap would also help to reduce uncertainty in the water balance and best keep track of usage for milk production.

For waste management, a nutrient analysis for both liquid and solid fractions of manure would help determine the influent on the urine treatment system and better quantify separation efficiencies from the screw press separator. Within the current urine treatment pH and oxygen sensors would help to better monitor biological processes and increase removal efficiencies. A flow meter for this system is also necessary to best control the influent into the intermediate bulk containers and control the hydraulic retention time.

For energy monitoring, it would be useful to create a document with major equipment used on the farm with basic information including energy ratings, or at least the make and model of equipment. This would help future researchers better quantify energy use and lead to less assumptions on a process level and a more accurate model.

6.2. Improvement Scenarios

As mentioned, the first priority recommendation to improve the circularity of the farm in terms of water management is to switch the compressor in the milk processing center from tap water to river water. It is encouraging that the process to accomplish this has already begun and that the FF has been proactive after the discovery of the large water loss. Also relevant for the current farm is to further investigate adding a multivalent ion such as aluminum sulfate or ferric chloride to increase P separation efficiency into the solid fraction of manure. Figuring out the current separation efficiencies by doing a nutrient analysis of the separated manure fractions would first be necessary and some experiments may be required to test which ion would be most efficient.

6.3. Future Research

The current farm is difficult/ expensive to change since it is already in operation, and the idea of FF is still a small-scale operation, but several scenarios investigated may be more reasonable for a future version of the farm. In the future, it would be worth researching using NF as an energy-efficient method of desalination. At the current scale, cons such as brine production and chemical use make the system less reasonable, but desalination may be a good solution for a future farm to become self-sufficient for water use. Also worth further investigation is anaerobic digestor technologies to help the farm become energy self-sufficient, increase separation efficiencies, and create renewable energy. At its current scale, the FF lacks operational expertise and the AD may not be cost-efficient, but the benefits of AD may be very useful in the future. Finally, it is recommended that the FF look into adding someone to their team with water treatment expertise to properly implement and expand water and waste management capabilities. Many solutions require full-time operational expertise in this area which the FF does not seem to currently have.

7

Conclusions

The large-scale industrialized linear economy of the last century has become increasingly unsustainable and contributed to climate change across the globe. The Netherlands has been at the front of the transition to a circular economy and set lofty goals for a more sustainable future. The agricultural sector has tried to follow and become circular but has struggled due to increased demand and a pivotal place in the Dutch economy. The sector is also specifically vulnerable to the effects of climate change and faces the challenge of being both climate-adaptive and maintaining demands. The world's first Floating Farm in Rotterdam aims to address this challenge by bringing food production into cities to shorten supply chains and land use.

In this study, the circularity performance of the Floating Farm's dairy production process was assessed and quantified. To determine circularity gaps and the contribution of different processes within milk production steps water, nutrient, and energy balances and circularity indicators based on the balances were derived based on the FF self-proclaimed circular actions. Indicator results were compared to a baseline farm when data was available. From identified circularity gaps four improvement scenarios were developed. The indicators were recalculated for each scenario and compared to the current model of the farm. Based on indicator performance and feasibility, recommendations for future steps to improve the farm's circularity were made.

Despite the farm's best efforts, the results of the mass balances revealed several gaps in circularity that were later confirmed by indicator calculations. The largest gap in circularity is the farm's water use and management. This gap stems from a reliance on the city water system, little water recovery, and the amount of wastewater. Only 2.71% of the FF's daily usage comes from rainwater. Currently, only 10% of water is recovered in products. Most of the water used is wasted leading to an overall waste index of 85% of inputs wasted. The once-through cooling used in milk processing is the largest contributor to the water wasted and makes the water used in milk processing per L of milk produced much higher than industry standards. Positively, once this gap was identified the FF was quick to take action to work to fix it before this report was even complete. In waste management, the biggest gap in circularity is the management of the liquid fraction of manure. Since it is currently put in the sewer, only 41.28% of N and 38.25% of P is recovered and most of the water in urine, and wash water in the barn is wasted. The electricity use on the farm is comparable to both industry standards and the baseline farm but performs poorly with the circularity indicators due to the reliance on the city system and the FF's inevitable small capacity to produce internally derived (solar) energy.

Also assessed were the impacts of processing milk on-site on transport emissions, and the impacts of using recycled feed from city waste. A small decrease in CO_2 emissions per L milk compared to the baseline was found, but the type of trucks used and the amount of waste exports made the decrease smaller than expected. The FF itself uses all-electric vehicles, but most feed imports still rely on urban transport trucks which have lower efficiencies than long-distance trucks used in typical farms. Using recycled feed drastically decreased land use compared to the baseline (by 99%), but this decrease has self-sufficiency trade-offs in terms of feed and energy and increases the need for the transport of waste. Feed cost per L milk was comparable to the baseline, but slightly more expensive for the FF (7.84% more expensive).

Scenarios for improving the once through cooling system in milk processing by using river water, desalination using NF, increasing recovery of water and nutrients in the liquid fraction of manure, and anaerobic digestion for renewable energy generation were assessed. Using river water for OTC was found to be feasible both technically and operationally. It greatly improves the performance of water and waste indicators. Desalination using NF was shown to be energy efficient, but concerns with chemicals for operation, and remineralization make the feasibility questionable for the FF due to its scale and water treatment operational capabilities. Precipitation of P before separation is feasible for the farm due to the simple operational needs and the possibility for high recovery. However, adding a denitrification step to increase the usability of water from the liquid fraction of manure may be difficult due to operational complexity and the need for a COD source. Installing an anaerobic digestor could produce more than enough energy to supply the whole farm, but questions of cost, and operational experience make it less feasible at this scale.

After the circularity assessment and scenario investigation, fixing the once-through cooling system in water processing is recommended as an urgent action for the FF. The system should be replaced, or the water source should be changed because the current system is creating significant water waste. The use of river water was deemed feasible and should be further investigated. The other three scenarios may be more of use for future versions of the farm.

A hindrance to making the most accurate conclusions about the FF's circularity is the lack of measured data at the farm. It is recommended that the FF work to install sensors to better indicate water use in each process. For waste management, a nutrient analysis of both the solid and liquid fractions of manure as well as feed inputs would help to better identify losses. The electricity use is better documented, but analysis and recording of electric ratings of equipment used would be beneficial for data collection in future work.

Furthermore, the Floating Farm has worked to implement circular actions into their innovative farm, but those actions have had varying degrees of impact on the farm's circularity as proven by circularity indicators. Overall, the farm's performance does not yet validate its self-proclaimed circular actions and there is still significant progress to make before achieving a circular economy. The FF's urban farming model has many trade-offs which are particularly evident in the farm's self-sufficiency and waste management. Nevertheless, the commitment to innovation and sustainability positions the Floating Farm as a valuable case study and a potential leader in the shift towards urban agricultural practices.

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A

Theoretical Background

A.1. Comparative analysis

Table A.1: Selected differences between sustainability and the Circular Economy from Geissdoerfer, Savaget, Bocken, *et al.*

Sustainability	**Circular Economy**	
Origins of the term	Environmental movements, NGOs, non-profit and intergovernmental agencies, principles in silviculture and cooperative systems	Different schools of thought like cradle-to-cradle, regulatory implementation by governments, lobbying by NGOs like the EMF, inclusion in political agendas, e.g. European Horizon 2020 Goals
Main motivation	Diffused and diverse reflexivity and adaptive past trajectories	Better use of resources, waste, leakage (from linear to circular)
What system is prioritized?	Triple bottom line (horizontal)	The economic system (hierarchical)
Who is Benefiting?	The environment, the economy, and society at large.	Economic actors are at the core, benefiting the economy and the environment. Society benefits from environmental improvements and certain add-ons and assumptions, like more manual labor or fairer taxation
How did they institutionalize (wide diffusion)?	Providing vague framing that can be adapted to different contexts and aspirations.	Emphasising economic and environmental benefits
Agency (Who influences? Who should influence?)	Diffused (priorities should be defined by all stakeholders)	Governments, companies, NGOs
Time frame of changes	Open-ended, sustain current status “indefinitely”	Theoretical limits to optimisation and practical ones to implementation could set input and leakage thresholds for the successful conclusion of the implementation of a Circular Economy
Perceptions of responsibilities	Responsibilities are shared, but not clearly defined	Private business and regulators/policymakers
Commitments, goals, and interests behind the use of the term	Interest alignment between stakeholders, e.g. less waste is good for the environment, organisational profits, and consumer prices	Economic/financial advantages for companies, and less resource consumption and pollution for the environment

B

Process flow diagrams

In order to quantify process flows and create mass balances and a model of the system, process flow diagrams including processes, input flows (green), processes losses (red) and product flows (purple) were derived. These flow diagrams are relevant to system development and circularity measurement steps in the circularity assessment framework.

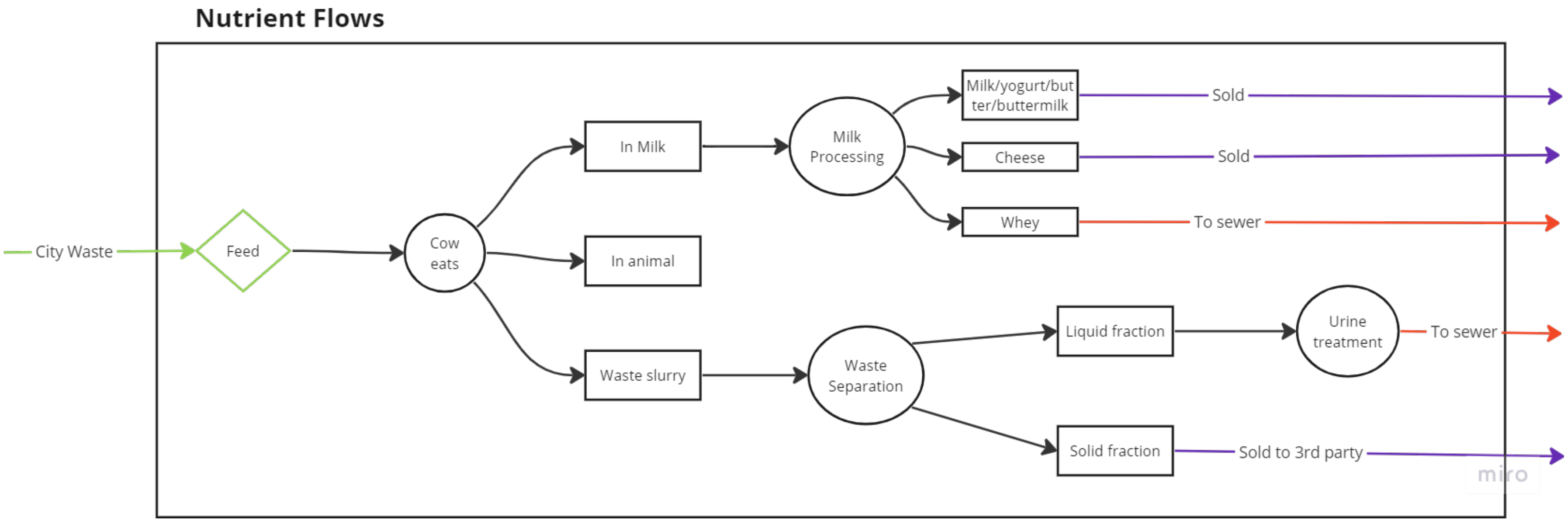


Figure B.1: Nutrient flows (relevant for N and P) of the system to be quantified

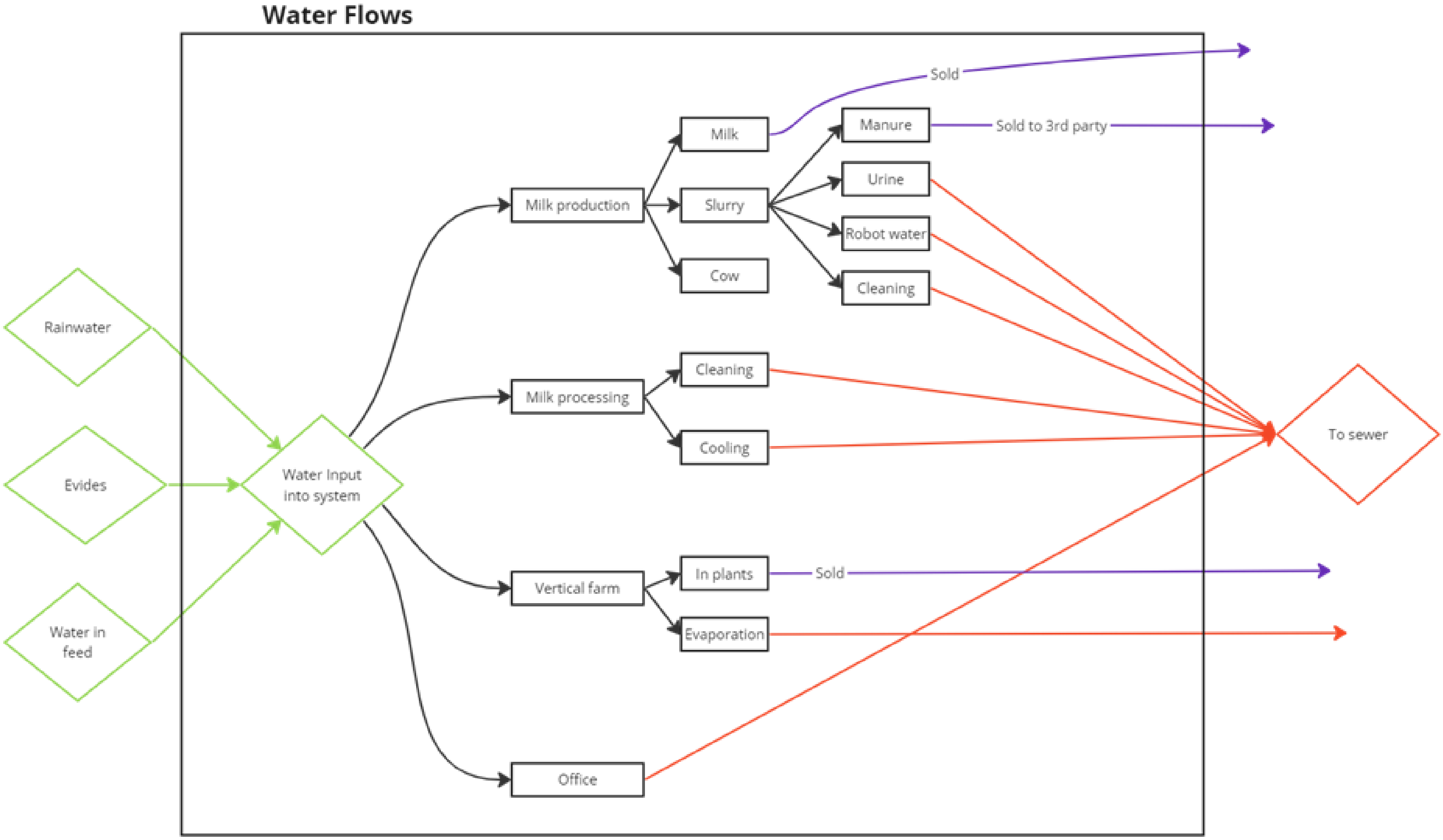


Figure B.2: Water flows of the system to be quantified

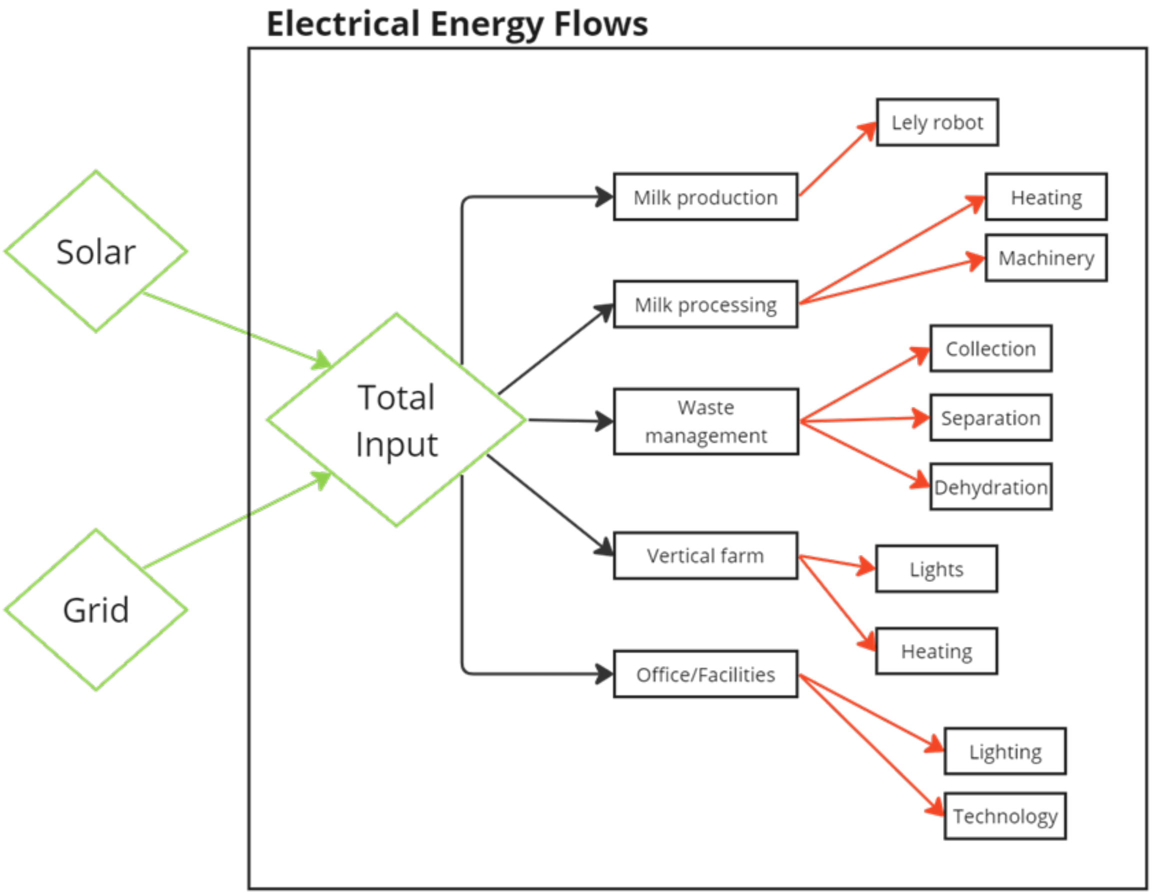


Figure B.3: Electrical energy flows of the system to be quantified

C

Data

C.1. Data for Indicators and Mass Balances

Table C.1: Veelon data from 2022 survey [26]

Attribute	Data Veelon Farm 2022
General	
Establishment Year	2002
Number of Dairy Cows	230
Milk production (L/day)	6200
Calves Born per Year	200
Retained Calves	55
Total Grazing Area (ha)	85
Grazing Area (ha)	50
Farm Inputs	
FOOD	
Total Feed (kg/day)	12500
	1. Beer residue
Origin	Jupiler Brewery
Transport	Trucks
Amount (kg/day)	600
	2. Silage grass
Origin	Grown on the farm
Transport	Self or grazing
Amount (kg/week)	3900
	3. Maize
Origin	Grown on the farm (half)
Transport	Electric vehicles for pickup
Amount (kg/day)	5500
	4. Feed Beets
Origin	Grown on the farm

Continued on next page

Table C.1 – continued from previous page

Attribute	**Data Veelon Farm 2022**
Transport	Self or grazing
Amount (kg/day)	1300
	5. Concentrate
Origin	Mills
Transport	Trucks
Amount (kg/day)	1200
WATER	
	1. Own Water Source
Drinking water	16000 L/day
Facilities	1200 L/day
ENERGY	
	1. Solar Panels
Amount	100000 Kwh/year
	2. Network Energy
Amount	55000 Kwh/year

Table C.2: Data for calculating nutrient, energy and water balances

General

Parameters from FF	**Amount**	**Unit**	**Source**
Number of Cows (used to normalize)	30	animals	FF
Milk produced (used to normalize)	24	L/day-cow	FF
Average weight of MRIJ cows	675	kg	FF

Nutrient Balance

Parameters from FF	**Amount**	**Unit**	**Source**
Nitrogen in liquid fraction	4.26	g N/kg	FF
Phosphorus in liquid fraction	0.96	g P/kg	FF
Manure produced	50	kg/cow-day	FF
Bierbostel feed	500	kg/day	FF
DDGS Proticorn	42	kg/day	FF
Grass	600	kg/day	FF
Dry weight Bierbostel	915	gDW/kg	FF
Dry weight DDGS Proticorn	903	gDW/kg	FF
Dry weight grass	450	gDW/kg	FF
% of milk used for cheese	10	%	FF
Parameters from Literature	**Amount**	**Unit**	**Source**
N in bierbostel	15	% crude protein	Shen, Abeynayake, Sun, *et al.* [27]
N in DDGS proticorn	27.15	% crude protein	Salim, Kruk, and Lee [30]
N in grass	2.29	% DW	Sánchez, Acuña, Inostroza, *et al.* [29]
P in bierbostel	6000	mg/kg feed	Shen, Abeynayake, Sun, *et al.* [27]
P in DDGS proticorn	10	mg/kg feed	Feedstuffs [28]
P in grass	0.41	% DW	Sánchez, Acuña, Inostroza, *et al.* [29]
CP conversion	CP is 16% N	%	Tillman [31]
Crude Protein in milk	3.7	%	Ruska and Jonkus [70]
Nitrogen in manure	3	%	Yan, Frost, Agnew, *et al.* [32]
P in manure	2	%	*Cow Manure Composting* [33]
Distribution of N and P after separation	N: 16% in solid fraction, 78% in liquid fraction, 6% lost in the barn P: 29% in solid fraction, 71% in liquid fraction	%	Aguirre-Villegas, Besson, and Larson [34]
NH3 lost after storage	18	%	Aguirre-Villegas, Besson, and Larson [34]
Whey to cheese percentage	10 to 1	proportion	Lopes, Eda, Andrade, *et al.* [35]
N in Whey	0.16	%	Wasserman [54]
P in Whey	300-600	mg P/kg whey	Robbins and Lehrsch [37]

Electricity Balance

Parameters from FF	**Amount**	**Unit**	**Source**
Network energy usage	1640.6 (on farm only)	kWh/month	FF

Solar energy from weather station	Month average 153.2	kWh/month	FF
Parameters from Literature	**Amount**	**Unit**	**Source**
Power for separator	3	watt	*Separators* [39]
Power for feed mixer	1.5	watt	Adusei-Bonsu, Amanor, Obeng, *et al.* [40]
Power for Lely Astronaut	0.126	kWh/milking/robot	Longtown [38]
Power for Lely Discovery	3	kWh/day	Longtown [38]
Water Balance			
Parameters from FF	**Amount**	**Unit**	**Source**
Rainwater collection area	625	m2	FF
Water for milking robot	4	m3/cow-year	FF
Evides water usage	18445	L/day From Mar 2023-Jan 2024	FF
Pressure washing frequency	Cow area washed 1-2 times a day, more frequently when it's hot		FF
Cleaning water (processing)	2000	L/day	FF
Cooling water (processing)	13698	L/day	FF
Cheese washing (processing)	300	L/day	FF
Parameters from Literature	**Amount**	**Unit**	**Source**
Rainfall per year	0.8	m	Instituut [42]
Evaporation per year	0.5	m	Schuetze and Chelleri [43]
Amount of Urine per day	10	L/d	Dirksen [71]
Pressure washing	400	L/hour	*What are the water supply requirements for a pressure washer?* [44]
Water in milk	87	%	*Milk* [45]

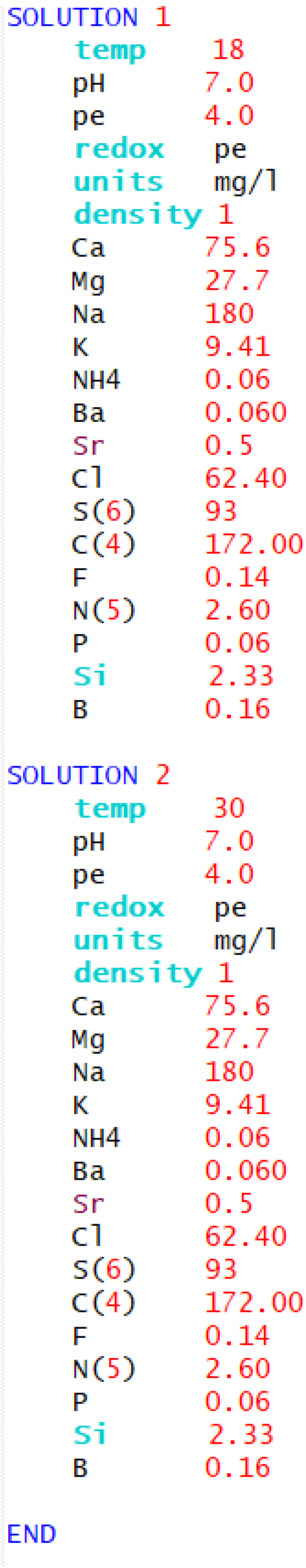
C.2. Cooling scenario

C.2.1. Water quality analysis

Table C.3: Ion Concentrations for Proposed Water Source

Parameter	Nieuwe Maas Concentration (mg/L)	Dutch DW Standard (mg/L) [58]	Implications for use in OTC
Ca	75.6	50	Water is naturally hard some scaling r isk
Mg	27.7	30	Water is naturally hard some scaling risk
Na	180	150	May cause scaling risk
K	9.41	12	Minimal impact on OTC
NH4	0.06	0.5	
Ba	0.06	0.7	
Sr	0.5	7	
CO3	0.133	2	
HCO3	172	250	
SO4	93	50	Can cause scaling and corrosion
Cl	62.4	150	Can cause pitting and corrosion
F	0.14	1.5	
NO3	2.6	50	
PO4	0.06	2	
SiO2	2.94	10	
B	0.16	0.3	

C.2.2. PHREEQC



```
SOLUTION 1
    temp     18
    pH      7.0
    pe      4.0
    redox    pe
    units    mg/l
    density 1
    Ca      75.6
    Mg      27.7
    Na      180
    K       9.41
    NH4     0.06
    Ba      0.060
    Sr      0.5
    Cl      62.40
    S(6)    93
    C(4)    172.00
    F       0.14
    N(5)    2.60
    P       0.06
    Si       2.33
    B       0.16

SOLUTION 2
    temp     30
    pH      7.0
    pe      4.0
    redox    pe
    units    mg/l
    density 1
    Ca      75.6
    Mg      27.7
    Na      180
    K       9.41
    NH4     0.06
    Ba      0.060
    Sr      0.5
    Cl      62.40
    S(6)    93
    C(4)    172.00
    F       0.14
    N(5)    2.60
    P       0.06
    Si       2.33
    B       0.16

END
```

Figure C.1: PHREEQC Model Input Code

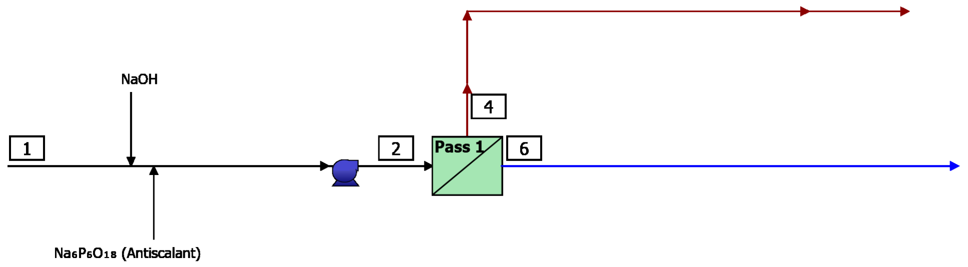
Table C.4: Full PHREEQC Results for 18 and 30 degree C

Saturation Indexes From PHREEQC model (Temp 18 degrees)			Saturation Indexes From PHREEQC model (Temp 30 degrees)		
Phase	**Formula**	**SI****	**Phase**	**Formula**	**SI****
Anhydrite	$CaSO_4$	-2.010	Anhydrite	$CaSO_4$	-1.900
Aragonite	$CaCO_3$	-0.750	Aragonite	$CaCO_3$	-0.570
Arcanite	K_2SO_4	-7.960	Arcanite	K_2SO_4	-8.140
Barite	$BaSO_4$	0.120	Barite	$BaSO_4$	-0.020
Calcite	$CaCO_3$	-0.610	Calcite	$CaCO_3$	-0.420
Celestite	$SrSO_4$	-2.060	Celestite	$SrSO_4$	-2.020
Chalcedony	SiO_2	-0.780	Chalcedony	SiO_2	-0.920
Chrysotile	$Mg_3Si_2O_5(OH)_4$	-8.930	Chrysotile	$Mg_3Si_2O_5(OH)_4$	-7.480
CO_2(g)	CO_2	-1.920	CO_2(g)	CO_2	-1.840
Dolomite	$CaMg(CO_3)_2$	-1.180	Dolomite	$CaMg(CO_3)_2$	-0.760
Epsomite	$MgSO_4{:}7H_2O$	-4.490	Epsomite	$MgSO_4{:}7H_2O$	-4.590
Fluorite	CaF_2	-2.760	Fluorite	CaF_2	-2.920
Gypsum	$CaSO_4{:}2H_2O$	-1.630	Gypsum	$CaSO_4{:}2H_2O$	-1.650
H_2(g)	H_2	-22.040	H_2(g)	H_2	-22.060
H_2O(g)	H_2O	-1.690	H_2O(g)	H_2O	-1.380
Halite	NaCl	-6.430	Halite	NaCl	-6.440
Hexahydrite	$MgSO_4{:}6H_2O$	-4.690	Hexahydrite	$MgSO_4{:}6H_2O$	-4.740
Hydroxyapatite	$Ca_5(PO_4)_3OH$	-3.180	Hydroxyapatite	$Ca_5(PO_4)_3OH$	-2.180
Kieserite	$MgSO_4$	-5.050	Kieserite	$MgSO_4$	-5.160
Mirabilite	$Na_2SO_4{:}10H_2O$	-5.810	Mirabilite	$Na_2SO_4{:}10H_2O$	-6.360
O_2(g)	O_2	-41.620	O_2(g)	O_2	-37.520
Quartz	SiO_2	-0.320	Quartz	SiO_2	-0.500
Sepiolite	$Mg_2Si_3O_{7.5}OH{:}3H_2O$	-7.200	Sepiolite	$Mg_2Si_3O_{7.5}OH{:}3H_2O$	-6.900
Sepiolite(d)	$Mg_2Si_3O_{7.5}OH{:}3H_2O$	-9.910	Sepiolite(d)	$Mg_2Si_3O_{7.5}OH{:}3H_2O$	-9.930
SiO_2(a)	SiO_2	-1.640	SiO_2(a)	SiO_2	-1.740
Strontianite	$SrCO_3$	-2.250	Strontianite	$SrCO_3$	-2.130
Sylvite	KCl	-7.010	Sylvite	KCl	-7.070
Talc	$Mg_3Si_4O_{10}(OH)_2$	-6.880	Talc	$Mg_3Si_4O_{10}(OH)_2$	-5.540
Thenardite	Na_2SO_4	-7.100	Thenardite	Na_2SO_4	-7.070
Witherite	$BaCO_3$	-4.050	Witherite	$BaCO_3$	-3.960

C.2.3. WAVE Report

RO Detailed Report

RO System Flow Diagram



#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	1.28	894.8	0.0
2	Net Feed to Pass 1	1.28	935.0	4.2
4	Total Concentrate from Pass 1	0.45	2,491	1.6
6	Net Product from RO System	0.83	95.42	0.0

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	65.0 %
System Flow Rate	(m^3/h)	Net Feed =	1.28	Net Product =	0.83		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Surface Water (SDI < 5)
Number of Elements		18
Total Active Area	(m^2)	46.8
Feed Flow per Pass	(m^3/h)	1.28
Feed TDS[a]	(mg/L)	935.0
Feed Pressure	(bar)	4.2
Flow Factor Per Stage		0.85, 0.85
Permeate Flow per Pass	(m^3/h)	0.83
Pass Average flux	(LMH)	17.8
Permeate TDS[a]	(mg/L)	95.42
Pass Recovery		64.8 %
Average NDP	(bar)	2
Specific Energy	(kWh/m^3)	0.23
Temperature	(°C)	25.0
pH		8.4 (After Adjustment)
Chemical Dose		3.0 mg/L $Na_6P_6O_{18}$ 21.7 mg/L NaOH
RO System Recovery		65.0 %
Net RO System Recovery		65.0%

Footnotes:

[a] Total Dissolved Solids includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	NF90-2540	2	6	1.28	0.00	3.9	0.0	0.58	2.9	1.0	0.70	22.4	0.0	69.12
2	NF90-2540	1	6	0.58	0.0	2.7	0.0	0.45	1.6	1.1	0.13	8.4	0.0	235.8

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)							
	Raw Feed	pH Adj. Feed	Concentrate		Permeate		
			Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.06	0.06	0.11	0.14	0.02	0.03	0.02
K^+	9.41	9.41	19.34	23.81	1.19	4.11	1.65
Na^+	180.0	192.4	396.6	489.3	23.71	80.02	32.59
Mg^{+2}	27.69	27.69	60.78	78.21	0.34	1.29	0.49
Ca^{+2}	75.58	75.58	165.7	213.1	1.04	4.07	1.52
Sr^{+2}	0.50	0.50	1.06	1.34	0.03	0.13	0.05
Ba^{+2}	0.06	0.06	0.13	0.16	0.00	0.02	0.01
CO_3^{-2}	0.18	5.23	13.66	18.50	0.00	0.01	0.00
HCO_3^-	172.0	194.5	421.8	540.1	3.27	12.59	4.74
NO_3^-	2.60	2.60	4.47	5.08	1.05	2.39	1.26
F^-	0.14	0.14	0.28	0.35	0.02	0.07	0.03
Cl^-	330.5	330.5	684.9	848.2	37.46	127.4	51.66
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	93.03	93.02	204.7	263.8	0.72	2.77	1.04
PO_4^{-3}	0.06	0.06	0.13	0.17	0.00	0.00	0.00
SiO_2	2.94	2.94	6.26	7.88	0.19	0.73	0.28
Boron	0.10	0.10	0.14	0.15	0.07	0.10	0.08
CO_2	20.85	0.94	1.96	2.51	1.16	1.94	1.28
TDS[a]	894.8	934.9	1,980	2,491	69.12	235.8	95.42
Cond. µS/cm	1,568	1,616	3,262	4,024	141	470	193
pH	7.0	8.4	8.4	8.4	6.6	7.0	6.7

Footnotes:

[a] Total Dissolved Solids includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Design Warnings

None

Special Comments

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	NF90-2540	11.7	0.64	3.9	935.0	0.57	0.07	28.8	40.88
1	2	NF90-2540	12.0	0.57	3.7	1,053	0.50	0.07	26.0	50.15
1	3	NF90-2540	12.3	0.50	3.5	1,189	0.44	0.06	23.4	61.74
1	4	NF90-2540	12.6	0.44	3.3	1,347	0.38	0.05	21.1	76.40
1	5	NF90-2540	12.8	0.38	3.1	1,528	0.33	0.05	18.8	95.13
1	6	NF90-2540	13.0	0.33	3.0	1,739	0.29	0.04	16.6	119.4
2	1	NF90-2540	5.9	0.58	2.7	1,980	0.55	0.03	13.2	152.1
2	2	NF90-2540	5.2	0.55	2.5	2,095	0.52	0.03	10.9	185.9
2	3	NF90-2540	4.5	0.52	2.3	2,200	0.49	0.02	8.9	227.4
2	4	NF90-2540	3.8	0.49	2.1	2,293	0.47	0.02	7.2	278.4
2	5	NF90-2540	3.1	0.47	1.9	2,372	0.46	0.01	5.7	341.0
2	6	NF90-2540	2.5	0.46	1.8	2,438	0.45	0.01	4.5	417.3

Footnotes:

[a] Total Dissolved Solids includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Langelier Saturation Index > 0	1
$BaSO_4$ (% saturation) > 100	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

RO Chemical Adjustments

	Pass 1 Feed before pH Adjust	Pass 1 Feed After pH Increase	RO 1st Pass Conc
pH	7.0	8.4	8.4
Langelier Saturation Index	-0.49	0.96	1.77
Stiff & Davis Stability Index	-0.09	1.4	1.80
TDS[a] (mg/l)	894.8	934.9	2,491
Ionic Strength (molal)	0.02	0.02	0.05
HCO_3^- (mg/L)	172.0	194.5	540.1
CO_2 (mg/l)	20.85	0.93	2.51
CO_3^{-2} (mg/L)	0.18	5.23	18.50
$CaSO_4$ (% saturation)	1.4	1.4	7.6
$BaSO_4$ (% saturation)	146.0	143.4	571.3
$SrSO_4$ (% saturation)	0.78	0.76	2.5
CaF_2 (% saturation)	0.17	0.16	1.6
SiO_2 (% saturation)	2.4	1.8	4.8
$Mg(OH)_2$ (% saturation)	0.00	0.10	0.29

Footnotes:

[a] Total Dissolved Solids includes ions, SiO_2 and B. It does not include NH_3 and CO_2

RO Utility and Chemical Costs

Service Water

	Flow Rate (m³/h)	Unit Cost ($/m³)	Hourly Cost ($/h)	Daily Cost ($/d)
Non-Product Feed Water				
Pass 1	0.5	0.1400	0.06	1.50
Total Non-product Feed Water Cost	0.5		0.06	1.50
Waste Water Disposal				
Pass 1	0.5	0.6900	0.31	7.41
Total Waste Water Disposal	0.5		0.31	7.41
Total Service Water Cost				8.91

Electricity

Peak Power	(kW)	0.2
Energy	(kWh/d)	4.5
Electricity Unit Cost	($/kWh)	0.0900
Electricity Cost	($/d)	0.4
Specific Energy	(kWh/m³)	0.23

Pump	Flow Rate (m³/h)	Power (kW)	Energy (kWh/d)	Cost ($/d)
Pass 1				
Feed	1.28	0.19	4.51	0.41
Pass 1 Total		0.19	4.51	0.41
System Total		0.19	4.51	0.41

Chemical

Chemical	Unit Cost ($/kg)	Dose 100% (mg/L)	Volume (L/d)	Cost ($/d)
$Na_6P_6O_{18}$(100%)(Pass 1)	1.000	3.0	0.0	0.09
NaOH (30%)	0.260			
Pass 1		21.7	1.7	0.58
Total Chemical Cost				0.7

Utility and Chemical Cost	($/d)	10.0
Specific Water Cost	($/m³)	0.501

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