Resource recovery of source separated sanitation compared to conventional system for sustainable urban wastewater management

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Abstract

Source separation sanitation offers an alternative for sustainable urban wastewater management by the possibility of energy and nutrient recovery, optimising the energy demand, saving and recycling water resources, and reducing the release of micropollutants to the environment. However, despite the well-developed infrastructure in urban areas, conventional sanitation has been questioned regarding sustainability due to upgrading systems for nutrient recovery efficiency, energy consumption, and environmental impacts.

The main goal of this study is to develop a comparative assessment tool for analysing sustainability criteria for concepts of conventional and source separation sanitation systems in terms of resource recovery potential.

The tool is developed through the SAmpSONS project. It is based on material flow analysis to individually track nutrient, energy, and wastewater flow. The output is evaluated based on Life Cycle Impact Assessment with indicators for energy demand, global warming, acidification, and eutrophication potential.

The related database for different technologies is structured in the database/library of the tool according to fundamental technologies of the wastewater treatment process and new technologies with the aim of resource (energy and nutrient) recovery, which can improve sustainability. The basic equations are based on the developed equations for the SAmpSONS tool. These equations are modified according to the set goals of this study.

The tool's outputs visualise the mass and nutrient flow as a diagram to present a holistic overview for each defined scenario. It provides a detailed calculation of each process unit's material flow, energy, cost, and related credit from recovery.

The comparison of conventional and source separation is carried out by defining ten scenarios, including scenarios for optimisation of sludge liquor treatment (R1), optimisation of sludge treatment (R2-R3), disposal route (R4), and nutrient recovery (R5-R6) from conventional wastewater and scenarios for alternative sanitation systems (S1-S3). The results are compared with the Reference scenario (R0).

Sustainability assessment is accomplished by developing a method for weighing and scoring ecological, economic, technical, and social criteria. The evaluation results show that none of the concepts is a premiere for all indicators; the results present a clear basis for decision making by pointing out which part can be optimised to reach the design goal. From the ecological aspect, there is an improvement by source separation sanitation concept (scenario S1-S3) compared to conventional scenarios (R0-R6). By contrast, the social part shows the decrease of score in source separation compared to conventional sanitation due to the unclear social impact of the source separation concept. Economic and technical aspects show the same flocculation in both concepts.

In general, the study indicates that the applied method can provide an appropriate tool for assessing the resource recovery efficiency from different sanitation concepts. It gives the possibility to examine the contribution of various sanitation processes in various aspects of sustainability.

Kurzfassung

Kreislauforientierte Stoffstromtrennungs- und -behandlungskonzepte bieten eine Alternative für ein nachhaltiges (urbanes) Abwassermanagement durch die Möglichkeit der Energie- und Nährstoffrückgewinnung, die Optimierung des Energiebedarfs, die Einsparung und Wiederverwendung von Wasserressourcen und die Emissionsminderung bei Mikroschadstoffen in der Umwelt. Diese Konzepte erheben den Anspruch besserer Nachhaltigkeit im Vergleich zum konventionellen Abwassersystem, jedoch sind diese Sanitärsysteme beim Umbau des nicht derzeitigen Systems im Hinblick auf die Steigerung der Nachhaltigkeitsindikatoren ohne große Veränderungen der gut ausgebauten Infrastruktur machbar.

Das Hauptaugenmerk dieser Studie liegt auf der Entwicklung eines vergleichenden Bewertungstools zur Analyse von Nachhaltigkeitskriterien für Konzepte der Stoffstromtrennung und der konventionellen Sanitärsysteme. Das Tool wurde im Rahmen des SAmpSONS-Projekts entwickelt und basiert auf einer Stoffstromanalyse, um Nährstoff-, Energie- und Abwasserströme individuell zu erfassen. Der Output wird auf Basis einer Ökobilanz mit Indikatoren für Energiebedarf, globale Erwärmung, Versauerung und Eutrophierungspotenzial bewertet.

Die zugehörige Datenbank für verschiedene Technologien ist in der Datenbank/Bibliothek des Tools nach grundlegenden Technologien des Abwasserbehandlungsprozesses und neuen Technologien mit dem Ziel der Ressourcen- (Energie- und Nährstoff-) Rückgewinnung strukturiert, die die Nachhaltigkeit verbessern können. Die grundlegenden Gleichungen basieren auf den entwickelten Gleichungen für das SAmpSONS-Tool, die entsprechend dem Ziel dieser Studie modifiziert wurden. Die Ergebnisdarstellungen des Tools visualisieren den Massen- und Nährstofffluss als Diagramm, um einen ganzheitlichen Überblick für jedes definierte Szenario aufzuzeigen. Die Nachhaltigkeitsbewertung basiert auf den definierten Kriterien.

Der Vergleich von konventioneller und Quellenabscheidung erfolgt durch die Definition von 10 Szenarien, darunter Szenarien für die Optimierung der Schlammabwasserbehandlung (R1), die Optimierung der Schlammbehandlung (R2-R3), des Entsorgungsweges (R4) und der Nährstoffrückgewinnung (R5-R6) aus konventionellem Abwasser und Szenarien für alternative Sanitärsysteme (S1-S3). Die Ergebnisse werden mit dem Referenzszenario (R0) verglichen.

Die Nachhaltigkeitsbewertung wurde mit der Abwägung und Bewertung von ökologischen, ökonomischen, technischen und sozialen Kriterien durchgeführt. Die Ergebnisse der Bewertung zeigen, dass nicht ein einzelnes Konzept in allen Indikatoren die besten Ergebnisse erzielt, jedoch ist durch die Auswertungen eine klare Entscheidungsgrundlage dafür verfügbar, welcher Teil optimiert werden kann, um das Planungsziel zu erreichen. Unter dem ökologischen Aspekt ergibt sich eine Verbesserung durch das Konzept der Stoffstromtrennung (Szenario S1-S3) im Vergleich zu den konventionellen Szenarien (R0-R6). Im Gegensatz dazu zeigt der soziale Aspekt eine Abnahme der Punktzahl bei der Stoffstromtrennung und -behandlung im Vergleich zur konventionellen Erfassung und Behandlung. Gründe hierfür sind Unsicherheiten und Skepsis gegenüber den sozialen Auswirkungen des Stoffstromtrennungskonzepts. Ökonomische und technische Aspekte zeigen bei beiden Konzepten ähnliche Ergebnisse.

Im Allgemeinen zeigt die Studie, dass die verwendete Methode ein gut anwendbares Tool für die Bewertung der Effizienz der Ressourcenrückgewinnung verschiedener Sanitärkonzepte sein kann. Sie bietet die Möglichkeit, den Beitrag verschiedener Prozesse der Siedlungswasserwirtschaft hinsichtlich der dargestellten Nachhaltigkeitsaspekte zu untersuchen.

Abbreviations and symbols

AD	Anaerobic Sludge Digestion
ASM	Activated Sludge Model
BG	Biogas
Bio-P	Biological Phosphorus Elimination
BOD	Biological Oxygen Demand
BW	Black Water
CED	Cumulative Energy Demand
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
d	Day
DM	Dry Matter (total solid content)
DWA	[de]: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall
EBPR	Enhanced Biological Phosphorus Removal
ES	Excess Sludge (secondary sludge)
FEP	Freshwater Eutrophication Potential
GaBi	Software-System und Datenbank zur Ganzheitlichen Bilanzierung
GBW	Garden Biowaste
GHG	Green House Gas
GK 1-5	Size Group (Treatment plant), [de]: Größenklasse (Kläranlagen) 1-5
GW	Grey Water
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
LCA	Life Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life Cycle Impact Assessment
LE	Leachate
MAP	Magnesium-Ammonium-Phosphate
MBR	Membrane bioreactor
MEP	Marine Eutrophication Potential
MFA	Material Flow Analysis
MFAR3	Material Flow Analysis for Reduce, Recovery, and Reuse from wastewater
NASS	New Sanitation System (de: Neuartige Sanitärsysteme)
NPK	Nitrogen (N), Phosphorus (P) and Potassium (K)
oDM	organic Dry Matter
PAM	Polyacrylamide
PE	Population Equivalent
PS	Primary sludge
PTGW	Pre-treated greywater
PTWW	Pre-treated wastewater
RW	Rainwater
SAmpSONS	[de]: Simulation und Visualisierung von Stoffströmen in neuartigen Sanitärsystemen
SBR	Sequencing Batch Reactor
SCST	Sanitation Concepts for Separate Treatment
SIMBA#	Name of a simulation system
SL	Sludge
SLD	Digested Sludge
SLT	Dried Sludge
SRT	Sludge Retention Time
SSA	Sewage Sludge Ash
TGW	Treated Greywater
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TS	Total Solids
U	Urine
VSS	volatile Suspended Solid
WWTP	Wastewater Treatment Plant
YW	Yellow Water
Z	Concentrate [de]: Zentrat

Contents

List of Tables

List of Figures

1 Introduction

1.1 Sustainability of urban sanitation management

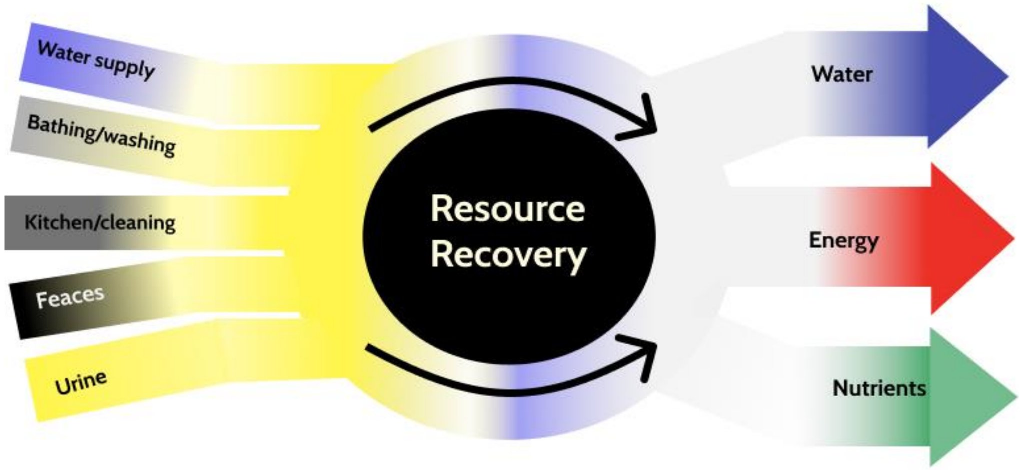
Sustainability in wastewater management is considered efficient and effective long-term water management. It provides human health and environmental protection and minimises energy and other resource demand and the nutrient cycle. This system should be economically viable, socially acceptable, and technically and institutionally appropriate (Kvarnström et al. 2004; SuSanA 2008; Spuhler et al. 2018)

The critical role of sanitation development was recognised in the Millennium Development Goals (MDG, UN, 2000). It was taken further in the Sustainable development Goals (SDGs) for 2030 (United Nations 2018) as a goal number 6 to ensure availability and sustainable management of clean water and sanitation for all.

The current sanitation system is designed to provide adequate and equitable sanitation and hygiene. Still, their operation has side effects on the environment due to construction, energy, chemical consumption, etc.

Wastewater contains valuable resources - including nutrients, energy, and water (Figure 1). On the other hand, wastewater treatment plants are among the main energy users in urban areas (Haberkern et al., 2008) to remove pollutants, mainly worth recovering. Particularly continuous growing global population, rapid urbanisation, and increasing social awareness of environmental aspects, e.g., climate change, shortage of natural resources, are driving to change the viewpoint towards the urban sanitation system. This point of view focuses on how wastewater systems can transform into resource recovery systems that are more economically and environmentally sustainable. Based on this concept, there is more focus on the sections of processes, which offer the potential for resource recovery.

The conventional sanitation system has been questioned regarding sustainability due to upgrading systems for nutrient recovery efficiency, energy consumption, water reuse, investment cost (Wilderer 2004). It emerges new challenges in reducing energy consumption, environmental impacts, and cost. Meanwhile, there is an increasing interest in optimising wastewater systems regarding improving sustainability. Further elaboration of this issue requires a close look at the functionality of the conventional sanitation system and its historical development.

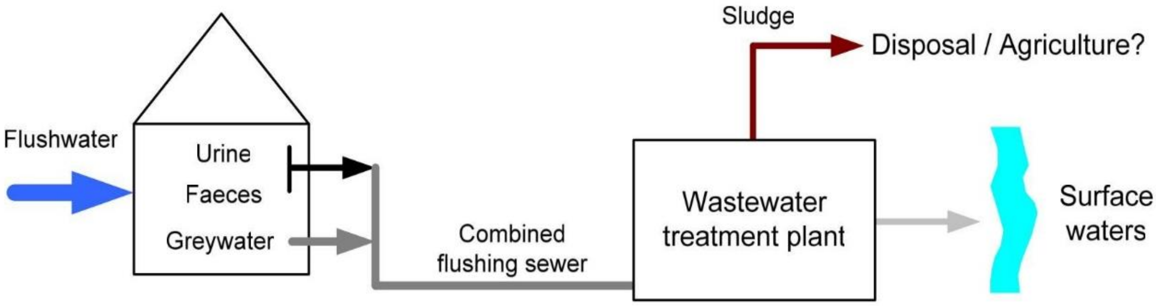


Source: Self-developed

Figure 1: Sustainable wastewater system

1.2 Development of the conventional sanitation system and drawbacks for sustainability

Conventional wastewater treatment combines all generated waste flows without considering nutrients (Figure 2). The mixture of domestic flow is transported to a central wastewater treatment plant (WWTP), where it is treated to regulatory standards before being released into the environment.



Source: (Remy 2010)

Figure 2: Conventional sanitation system of urban wastewater management

In conventional wastewater treatment, nutrients are diluted in a large volume of mixed wastewater, and their recovery is economically less feasible. Energy and nutrient recovery from diluted sewage in terms of organic matter of total stream is also less attractive than of highly concentrated flow (Kujawa-Roeleveld und Zeeman 2006).

In this circumstance, energy is used to get rid of nutrients and then consumed energy to produce fertiliser as a required nutrient for agriculture. Wastewater has the potential to be used as a fertiliser before mixing with heavy metals, pharmaceuticals, and industry insolvent. The mixing of wastewater in current systems makes it unprofitable to extract valuable nutrients from highly polluted wastewater. Therefore, most nutrients are disposed to a landfill or incinerated (Lendrum 2015).

This system provides a limited possibility for wastewater recovery due to the dilution and complexity of recycling valuable nutrients. Breaking the nutrient cycle is an outcome of conventional wastewater treatment, which is unsustainable. Therefore, this system occupies high energy and chemical demand of wastewater treatment plants that may be questioned regarding sustainability criteria (Remy und Jekel 2008).

The efforts for optimizing the conventional system have been increased in recent years in terms of sustainability. It primarily focuses on decreasing direct electrical energy demand, greenhouse gas emission, and increasing biogas production. The final vision of the urban sanitation system is an energy self-sufficient or even energy positive process, which fulfils the appropriate standard on effluent quality regarding sustainability criteria. However, the indirect effects of the optimisation on various methods may have negatively influenced the overall energy balance and environmental footprint that still require more research and observation (Remy 2012a).

The present infrastructure for water supply and wastewater disposal does not meet the criteria of sustainability and resource efficiency because of its systemic ecological and economic deficits. Sustainable ecological sanitation introduced the "source separation sanitation system" concept as an alternative and enhancement to conventional water infrastructure. The separation of black- and greywater requires appropriate treatment options so that these ecological sanitation systems can develop to their full potential.

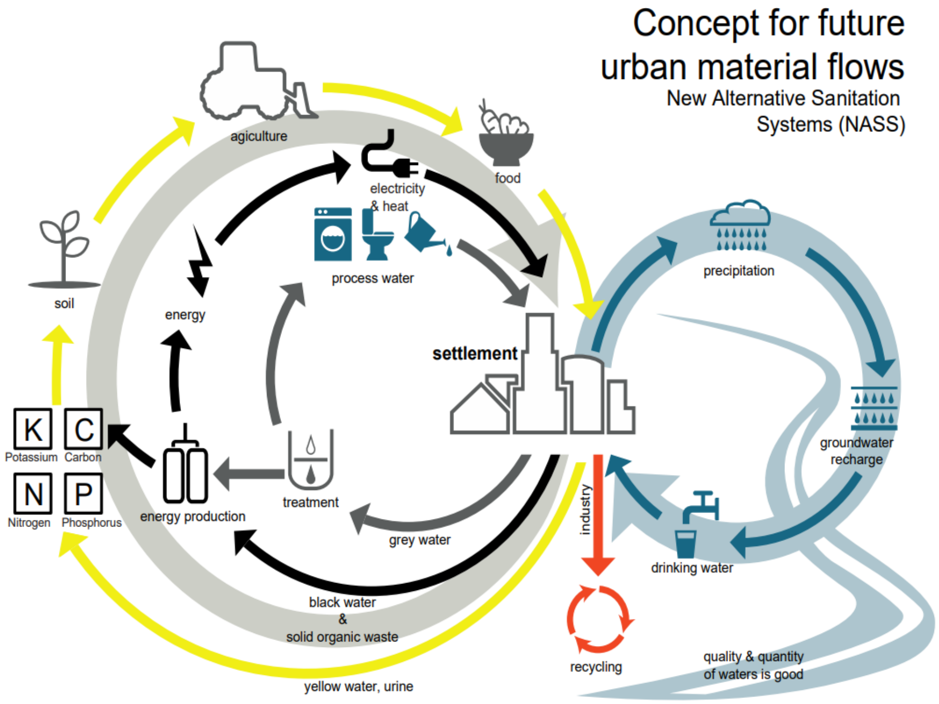
Within the concept of sustainable development, it is necessary to shift towards closed-loop management (Meinzinger 2010). Hence, nutrient recovery for agriculture increased energy efficiency and protected natural water resources, contributing to a more efficient sanitation system.

1.3 Source separation system, a sustainable approach for urban sanitation challenges

Source separated sanitation offers the possibility of recovering nutrients, increasing efficient water recycling, and reducing the release of micro-pollutant to the environment compared to conventional wastewater treatment (Bachmann 2015; Elmitwalli und Otterpohl 2007; Langergraber und Muellegger 2005; Larsen et al. 2013; Lindner 2007; Remy 2010; Wätzel und Kraft 2014b; Balkema 2003; Zeeman et al. 2008; Wilsenach et al. 2003).

According to the source-separated sanitation idea, faeces, urine, and wastewater from the bathroom and kitchen differ significantly in nutrient, chemical, and biological content (Figure 3). The separation of these wastewater streams provides the opportunity for individualized treatment of each flow to maximize water reuse, capture nutrients, and minimize energy input for wastewater management.

Source separation has become attractive to environmental and wastewater process engineers because, although urine is only 1% of domestic sewage, it contains 50-80% of the nutrients and a majority of excreted pharmaceuticals and hormones (Fewless 2015). Separating the relatively small fraction of these flows can enable a more efficient treatment process in terms of resource recovery (Remy und Jekel 2008).



Source:(Londong und Maier 2016)

Figure 3: Overview of source-separated sanitation system

Despite that separation of various types of wastewater from source has been recognized as one of the promising sanitation concepts towards providing sustainability criteria in the area of wastewater management in recent last decades (Zeeman und Lettinga 1999; Wilsenach et al. 2003; Otterpohl et al. 2004; Peter-Fröhlich et al. 2007; Larsen et al. 2009; Meinzinger und Oldenburg 2009; Remy 2010; Tervahauta et al. 2013) it is not implemented often until now due to the following barriers:

- The technological challenges are complex in terms of implementation and more intricate physical connections of a sustainable system
- Decision making is complex due to the involvement of a diverse group of users with various levels of understanding of sustainable concepts
- The management is more complicated regarding maintenance and operation
- The risk and unintended consequence of implementing this concept on a large scale is unknown and compared to well-developed conventional sanitation system is immature
- Quantitative evidence of the sustainability criteria for comparison of source separation and conventional sanitation system is scared

- The cost analysis is challenging; in the first estimation, this system has a higher investment cost compared to a conventional system, and on the other side, the benefit of source separation due to the lack of data is not easy to calculate

Since a sustainable urban sanitation system is becoming an essential objective of decision-makers of the communities, providing the simultaneous comparison of source-separated sanitation concept with conventional sanitation by visualization of different aspects would be one more step forward for optimizing the strategies of cities for the future.

For accurate sustainability criteria analysis, it is necessary to compare source separation and current sanitation systems in different aspects. Energy and water use are significant factors, but nutrients, contaminants, and purification capacity will also play an essential role in executing this analysis (e.g., considering the environmental harm of releasing excess nutrients and micropollutants into the environment). A good starting point would be considering the possibility of equal comparison of conventional and source-separated sanitation concepts in terms of sustainability.

1.4 Definition of the objectives

The main goal of this study is to provide a suitable platform to compare source separation sanitation with the conventional system in terms of sustainability criteria. It evolves to investigate technical, ecological, economic, and briefly social aspects of sustainable wastewater management for both systems.

This research aims to develop a model that can be a reference for the various alternatives of source-separated and conventional concepts that decision-makers can simulate and evaluate various alternative sanitation concepts to assess the efficiency of nutrient recovery, energy production, and elimination of micro-pollutant. The specific goals of this model are to emphasize the following processes, which can result in sustainability:

- Nutrient and energy recovery potential process
- Water conservation
- Global warming, acidification, and eutrophication as an ecological sustainability indicator
- Economic and social indicator

Considering these processes in the developed model, selecting an optimal decision between conventional and source separation sanitation systems is expected. It achieves adequate water quality levels at the affluent and additional aspects such as operational safety, cost - with particular attention to energy requirement- and the environmental impact relative to greenhouse gases and other emissions to water and soil.

The outcome of this work is expected to increase knowledge of the source separation sanitation system and identify the drawbacks of the conventional system to improve the efficiency of the urban sanitation system by contributing to strategic planning and systematic analysis.

2 Historical development of sanitation concepts

2.1 Review of source separation concept towards conventional sanitation system

Source separation concept has been investigated since the 1990s, but mostly considered as an inexpensive and environmentally friendly concept in the rural and under-developed areas (Jönsson et al. 1997; Otterpohl et al. 1997; Londong und Otterpohl 2001; Norström et al. 2008; Lienert und Larsen 2010; Larsen et al. 2009; Barjenbruch 2012; Horn et al. 2013; Istenic et al. 2015).

Several studies have investigated source separation technologies for urine, blackwater, and greywater, in lab-scale (Larsen und Gujer 1996; Al-Baz et al. 2008; Maurer et al. 2006; Tettenborn 2011; Burgada Ruiz 2016). Hence several groups started working on source separation out of the lab, focusing on urban sanitation (Peter-Fröhlich et al. 2007; Lamine et al. 2007; Oldenburg 2007; Li et al. 2009; Chong et al. 2012) as an alternative to existing end-of-pipe systems.

The pilot implementation has been installed worldwide (DWA 2008; SuSanA 2008), including various technologies and approaches. Despite the diversity of the approaches, their common goal is to fulfil sanitation needs, not only to focus on hygiene and health issues but also to contribute to the sustainable management of wastewater.

The source separation studies review can be classified as overarching studies, specific technologies, and specific products.

-The overarching case studies

A few pilot plants were built to achieve experience in installation, operation, maintenance of the different components of source-separated sanitation and social acceptance of this system. For instance, Stahnsdorf pilot plant in Berlin which was owned and operated by the Berlin Wasserbetriebe (SCST,2006), Lübeck, Flinterbreite housing development, Hamburg Water Cycle pilot in Jenfelder Au (Augustin et al. 2014) and pilot plant in Sneek in the Netherlands and Understenshöjden pilot plant in Sweden. The focus in these pilot projects is set based on the defined goal of the study. Overview of these pilot plants and related information is shown in Table 1.

- Focus on the specific processes and technologies

These kinds of pilot projects focus on specific technologies like anaerobic digestion for blackwater or reuse of greywater, the functionality of Urine-Diverting (UD) toilets (GIZ ecosan program, Eawag office building, NOVOQUATIS project in Switzerland). Some projects have only tested the functionality of source separation technologies. Even though the technical feasibility of source-separated sanitation systems in different pilot projects has been successfully proved, there is still a lack of performance to more resource-oriented sanitation concepts (DWA 2009; Larsen et al. 2009Guest et al. 2009).

-Focus on the specific products

Various pilot projects have attempted to implement a source separation system towards maximizing resource recovery efficiency; by producing fertiliser from recovered N and P, energy recovery from blackwater, and water reuse from greywater. These projects are often limited in their system boundary, the scale of implementation, and choice of technologies which is a barrier to using their finding on bigger scales.

2.2 Reviewing the sustainability concept in the context of urban sanitation

Developing a comprehensive methodology for assessing sustainability for different sanitation systems investigated in several studies (i.e., Ellis und Tang 1991; Otterpohl et al. 1997; Hellström et al. 2000; Balkema et al. 2002; Remy und Jekel 2008).

Different dimensions of sustainability and corresponded indicators (up to 30) are considered for evaluating water systems (Hügel 2003, leading to the complexity of comparing different systems and achieving a specific result.

Quantitative methods such as Material flow analysis (MFA), Life Cycle Assessment (LCA), Material Input per Service Unit (MIPS), etc., have been used to assist the choice of distinct solutions under defined conditions (Makropoulos et al. 2008; Benetto et al. 2009).

These methods can be defined based on the under-investigation system as product-oriented, material-oriented, and monetary-oriented methods (Cote 2016). Product-oriented methods investigate products and their effects on the environment, such as LCA (ISO, 2006) and MIPS (Liedtke et al., 2014). The material-oriented method allows the study of the flow of materials being used and transformed within a system defined in space and time like Environmental Input-Output Analysis (EIO) (Tukker und Jansen 2006), Waste Input-Output Analysis (WIO) (Nakamura et al. 2007), Ecological Footprint Analysis (EFA) (von Gleich and Gößling-Reismann, 2008), MFA (Brunner und Rechberger 2002).

Table 2 summarizes the main attributes of each discussed method. Not all are suitable for assessing various inclusive aspects of sustainability from the abovementioned methods. Nevertheless, in the last decades, the application of these methods has focused mainly on an environmental level. LCA has been used as an appropriate tool for a systematic investigation of the environmental impacts of wastewater systems (Lundin 2002; Mühleck et al., 2003; Siegenthaler, 2006; Klöpffer and Grahl, 2009; Remy, 2010).

Table 1: Overview of selected pilot plants in Europe for source separation concept

Project	Location	Year	Inhabitants	Driver	Reference	Special focus
SCST-Stahnsdorf	Berlin	2003-2006	10 Apartment, 1 operation building	Wasser Berlin	Peter-Fröhlich et al. 2007	Optimisation of components
GIZ building,	Eschborn	2006- up to now	50 NoMiX toilets	GIZ	www.giz.de	Demonstration
Flinternbreite	Lübeck	1999-up to now	117 households	University	Oldenburg 2007; SuSanA 2008	Anaerobic digestion, Recycling to agriculture
Jenfelder Au	Hamburg	Construction phase, from 2018 in operation	630 households	Hamburg Wasser	Augustin et al. 2014	Optimisation of components
Allermöhe	Hamburg	1985-up to now	140 single houses	Susana	www.susana.org	Eco-village
Understenshöjden	Stockhol m	1997-2000	44 apartments	Stockholm Water Company	Johansson et al. 2000	Eco-village
Lemmerweg Ost	Sneek	2003-2010	32 houses	Manufacturer	http://nieuwesanitati e.stowa.nl	Vacuum toilets and anaerobic digestion
Lambertsmühle	Burscheid	2001-2003		Otterwasser	www.burscheid.de/d e	Establish a local nutrient and water cycle for source-separated flow
Block 6	Berlin	1989-up to now	70 residents	Nolde and partner	http://www.stadtentw icklung.berlin.de	Integrated water concept with greywater recycling and industrial water use
Linz	Austria		-*	Solar City	www.linz.at/leben/4.	Separate collection and treatment of the partial flows' urine, brown water, and greywater

*No data available

According to the mentioned methods, the MFA method is the most appropriate and indicated method for the interest and objective of this work. Since it can systematically evaluate material and energy balance and quantitatively allocate materials, it can be integrated with other methods to provide the goal of this study. Often an MFA is the basis for LCA, and the LCA inventory step can be established through an MFA. Hence, the LCA can convert from a product-oriented to a broader system analysis (Brunner und Rechberger 2002). In addition, it can be used at economy-wide levels for a dynamic perspective.

The drawback of the LCA method is the restricted assessment by the system boundaries. For example, changes in the system, such as changes in demand, are not easily accounted for (Remy, 2010). It means that dynamic development processes such as urban development, like changes in demographics, are challenging to incorporate since only standardized conditions are used.

Table 2: The overview of the methods used for evaluation of different sanitation systems

Method	Reference	Resource volume	Manufacturing	Product market	Waste market	Final use phase	Waste treatment process	Emission volume	Dynamic
MFA	Brunner und Rechberger 2002	x	x	x	x	x	x	x	x
LCA	ISO 14040	x	x	-	-	x	x	x	-
WIO	Nakamura et al. 2007	-	x	x	x	x	x	x	-
EIO	Tukker and Jansen 2006	x	x	x	-	-	x	x	-
EFA	Gößling-Reisemann 2008	x	-	x	-	-	-	x	-
MIPS	Liedtke et al. 2014	x	-	-	-	-	-	x	-

The use of this method as an appropriate tool for the sustainability assessment of wastewater management systems has been systematically investigated in the various study (Bengtsson et al. 1997; Roeleveld et al. 1997; Tillman et al. 1998; Schneidmadl et al. 2000; Jeppsson and Hellström 2002; Mühleck et al. 2003; Hospido et al. 2004; Lundie et al. 2004; Lassaux et al. 2007; Benetto et al. 2009; Remy 2010; Godin et al. 2012; Garrido-Baserba et al. 2014; Bisinella de Faria et al. 2015; Larrey-Lassalle et al. 2017).

The monetary-oriented methods are Input-Output Analysis (IO), Life Cycle Cost (LCC), Cost-Benefit Analysis (CBA) (Hernandez-Sancho et al. 2011), and Cost-Effectiveness Analysis (CEA) (Dockhorn 2007b) which can be applied for system comparison.

Although the concept of LCC (WCED 1987; Rebitzer et al. 2003; Remy 2010) would be an ideal concept to assess all parts of economic factor including the capital, operation, maintenance, revenue, and disposal cost, the related data for the economic assessment of sanitation system, especially source separation system is scared in general and are difficult to find in the scientific literature. Valid cost data for the source separation system is limited to small pilot plants, and the upscaling of cost leads to rough calculation. Reporting from other cost analysis studies (Oldenburg 2007) shows the costs highly depend on the local conditions, e.g., energy and water price and population density.

A combination of cost-effectiveness and cost-benefit analysis and an MFA is introduced for a waste management assessment by Döberl et al. (2002) and developed further by Meinzinger (2010) for source separation concepts. In principle, all kinds of costs and benefits could be included in a cost analysis. However, social and environmental costs or benefits (i.e., intangibles) are usually difficult to quantify and often not included in economic evaluations. In general, valid cost data for a large-scale, especially for the source-separated concept, is not available; therefore, data from the smaller pilot plant must be applied as a basis for cost analysis with uncertainty.

Simultaneously to the development of methods for sustainability assessment of sanitation systems, different software tools are extended to calculate the various aspects of these systems. It is ranged from the simplified calculation of each process in spreadsheets of Microsoft Excel to some software tools specifically designed for this goal, such as, e.g., Substance Flow Analysis (STAN) developed by Vienna University of Technology, the Swedish MFA application in waste management called ORWARE (Jeppson and Hellström, 2002), the software SIMBOX (Bader and Baccini, 1996, Meinzinger, 2010) and Santiago (Spuhler et al. 2020) developed by EAWAG (Switzerland). Since this software is developed based on their goals, the Eawag is mainly created for developing countries, not developed areas. Hence, the goal of this study is to develop a tool that can cover other aspects of sustainability.

3 Methodology

3.1 The outline of the research method for sustainability evaluation

In order to evaluate the sustainability indicators for various wastewater management systems, which allow resource recovery, the methodology of this study is the integration of the material flow analysis with their corresponded sustainability criteria. The methodology provides the modelling of nutrient, energy, and cost and their sustainability criteria in direct connection of variation of the defined wastewater flow in different defined scenarios. It attempts to combine the relevant mentioned issues from former studies, which have been discussed in the literature review chapter (Section 2.1).

In detail, the following steps are implemented:

- Determine the difference between conventional and source separation concepts in the sanitation system
- Definition of each sanitation system based on specific objective including the definition of system boundaries, flows, material, and processes
- Identification of sustainability criteria for each process based on different flows
- Selection of processes and technologies, which lead to resource recovery
- Data collection
- Establishing a set of equations to represent the behaviour of each concept
- Set up different scenarios or the possibility of the systems for resource recovery
- Simulation runs include calibration, uncertainty
- Analysis based on technical data in combination with interpretive and qualitative research method

3.2 The approach of this study

The approach of this study is the development of a mathematical model, which integrates the mass, nutrient flow, energy flow, and cost estimates of wastewater systems to assess sustainability criteria.

It attempts to combine all relevant parameters, which allow the modelling of sustainability criteria directly correlated by varying material flow and energy in each system.

This collection of different systems allows the comparison and the assessment of sustainability criteria in various possible source separation alternatives versus conventional sanitation systems.

The principle of this model is based on the classical “Material Flow Analysis” method due to its comprehensive approach and the possibility of extension for a combination of energy balance and cost estimates.

This method is called "MFAR3" in the context of this study based on using material flow analysis for the process of Reduce, Recovery, and Reuse from wastewater.

The foundation of the model is the modelling of mass and nutrient flows. Mass flow includes wastewater flows, nutrient, energy, and chemicals demands in treatment processes that pass through different processes until return to nature. Therefore, the sustainability assessment of processes would be possible if each process unit is defined based on influent, effluent, and corresponding required material, energy, and cost characteristics. Figure 4 shows the schematic diagram of a one-process unit based on corresponding information. The assessment process has been done based on the procedure presented in Figure 5.

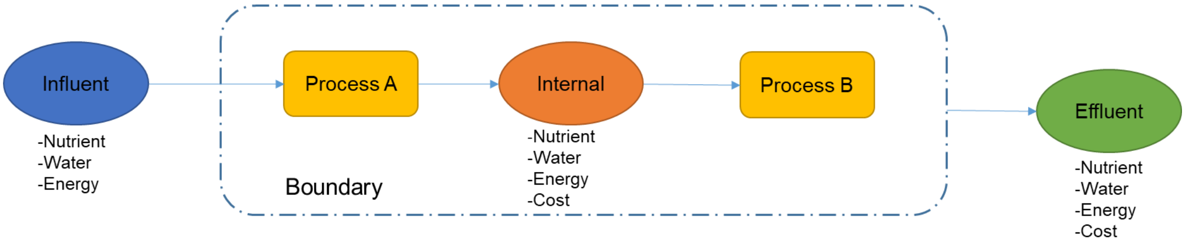


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Figure 4: The schematic of nutrient, energy flow, and cost in a process unit

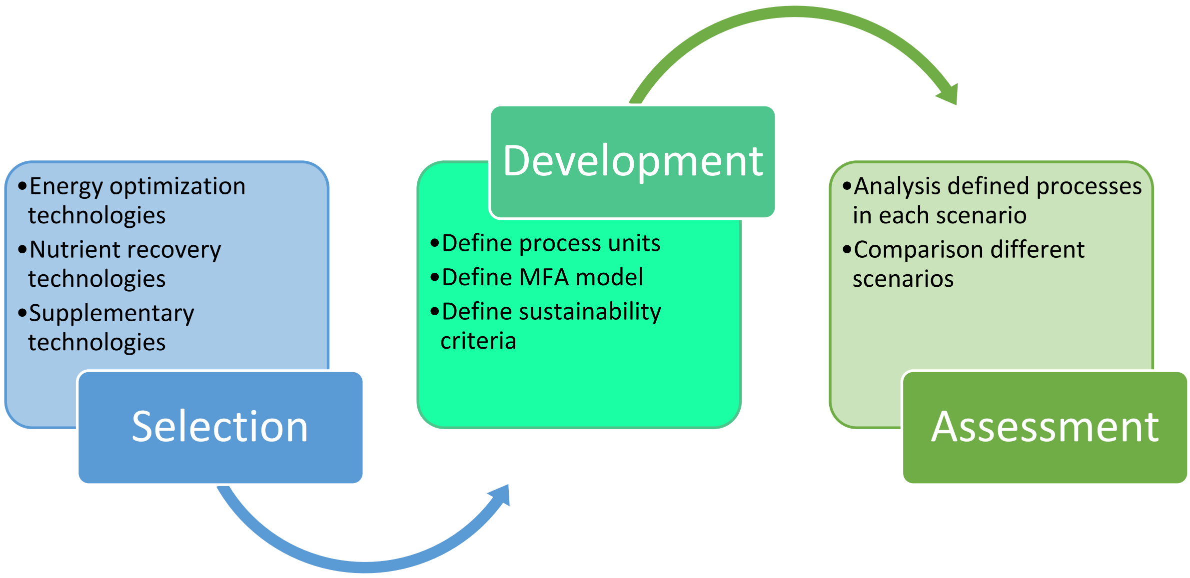

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Figure 5: The process of assessment in the MFAR3 method

In the MFAR3 method, nutrient, energy flow, and cost estimates are transferred into mathematical models by formulating system equations (more detail about equations in section 3.9). First, the required wastewater treatment process units emphasizing process, which leads to nutrient /energy production, are selected. The required character of different flows is set up for each flow and each process.

The inventory list of LCA is used to evaluate sustainability criteria for different wastewater management processes (Ortiz et al., 2007). Since the LCA analysis has been done by Remy (2010) for source separation system, this study is using the result of this study for further investigation of ecological aspect and the cost analysis is adapted from Meinzinger (2010) and the primary reference for the social aspect is SCST (2007).

As figure 6 shows the functionality of the model, this mathematical method is established based on the combination of the following analysis model to achieve the assessment for the sustainability of sanitation:

The material flow analysis model is carried out to model nutrient and wastewater flow by formulating system equations for different processes and transferring the required criteria into mathematical equations. The exact process is applied for transferring the energy flow and cost estimation. In detail, the following main steps are implemented:

- Building up a basic system framework for the specific goals: nutrient recovery, energy balance. It includes the definition of system boundaries, flows, and substances to be considered and the relevant processes:
- Definition of sustainability criteria in wastewater management by describing which criteria and why it is crucial for this analysis
- Data collection includes identifying which data are needed and how these data are collected
- Characterization of different wastewater flows (blackwater, greywater, yellow water, and mixed wastewater in urban areas)
- Developing the equation systems to describe the system behaviour
- Simulation runs include calibration, uncertainty, and sensitivity analysis
- Analysis, interpretation of the results

The concept of this method allows the modelling with uncertain data (based on the introduced model by Baccini and Bader, 1995), which provides a suitable model for the concept of source separation with many lacks data. Therefore, data from literature values complemented by reasonable estimations can be used instead of data from extensive measurement (Schaffner 2007, Meinzinger, 2010).

3.3 Definition of boundary conditions and process units in the system

The defined sanitation system is specified by relevant flows and processes involved in urban sanitation concepts. A sanitation system is a set of processes, which manage and treat wastewater flows from the source of generation to the final point of disposal or reuse.

Processes can be defined as activities that collect, transport, store material, treat, and recover. Flows provide the linkage between processes. Flows include the mass flow of wastewater and nutrients, and chemicals.

Each process called in this study "process unit" is defined using the influent, effluent, and transformation data, including the functional and mass balance of nutrients and flows. Figure 6 shows the schematic of each element of one process unit.

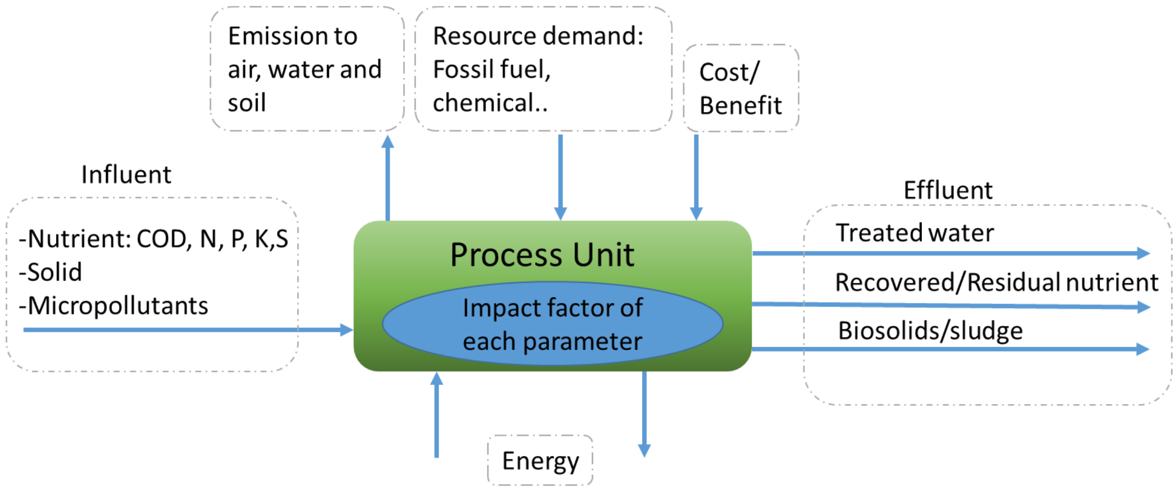

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Figure 6: Process unit which identified each process

- Influent: Parameters that define the nutrient and wastewater characteristics at the input of the process unit to fulfil its function within the overall process. The selected nutrient (organic and inorganic) can represent various compound forms in the urban wastewater system. Nitrogen (N), Phosphor (P), Potassium (K), and Sulphur (S) are considered nutrients due to their relevance for nutrient recovery and environmental impact of sustainability. Furthermore, organic carbon (COD) determines the quality of wastewater because of its role as a pollutant of surface water and its importance for energy production. Besides, it plays a significant role in soil conditioner in agriculture. These compounds usually show dynamic properties in different scales, which is not easy to reflect on the selected modelling approach since the focus of this study is the system's overall performance; the assumption is set to a steady property of parameters in each process unit.

- Effluent: Information about the expected effluent properties by indicating the performance of any process, including the treated water, the nutrient that discharged as a recovered or disposed of material/ nutrient
- Impact factor: information of possible impacts that a process unit can cause in terms of sustainability indicator (GHG, EP, PE ...) by emission to water, air, and soil
- Energy: information on energy demand and specifically the production of energy
- Cost: information about the main cost in each process unit, including investment, operation cost, energy demand

The process unit and flows are linked in a set of equations (more detailed explanation in section 3.9) to reflect the urban sanitation system.

The system's boundary should be selected to guarantee the fulfilment of the research goals for a proper comparison while keeping the system manageable in terms of data collection and complexity.

The processes included in the system boundary must represent a series of actions that present a particular service. In the context of this study, the aimed service is on the process with the potential of water-saving, nutrient, and energy recovery from urban sanitation systems.

Two inner and outer boundary levels consider boundary conditions in this study. The inner boundary considers the process of wastewater treatment from the household to disposal, which is directly involved. The outer boundary is considered indirectly related to the wastewater process, such as water supply, mineral fertiliser production, and incineration as a disposal route.

Figure 7 gives an overview of the processes and flows included in this study. A continuous line specifies the system boundary, and the dotted line represents the prototype of processes in this thesis. According to this prototype, urban sanitation is classified into five functional groups (FGs)[1]: collection, storage, transport, treatment, disposal, or reuse.

Overall, the following general process is considered in the system boundary:

- Households for the unit for generating wastewater flow
- Water supply demand
- Domestic sanitation includes wastewater treatment by the activated sludge process[2] (Remy und Ruhland 2006), Sludge treatment including anaerobic digestion, dewatering, drying, and incineration; Biogas from the digestion process is combusted in a Central Heating and Power plant (CHP) to produce electrical and thermal energy.
- Transport
- Nutrient recovery units
- Reuse/disposal as an end of the process

[1] The name of Functional Group adapted from (Tilley et al. 2014)

[2] Activated sludge process with nitrification and denitrification is considered as a typical process for wastewater treatment in Germany.

Due to the various possibility for each functional group, there would be numerous combinations of different facilities. However, these technologies facilitate more flexibility and can provide resource recovery but also, the decision-making process is becoming more complicated. It has become even more complicated by the advent of many novel technologies in recent years.

Therefore, it is essential to cope with this difficulty by choosing a systematic option selection, which will be discussed in the next section.

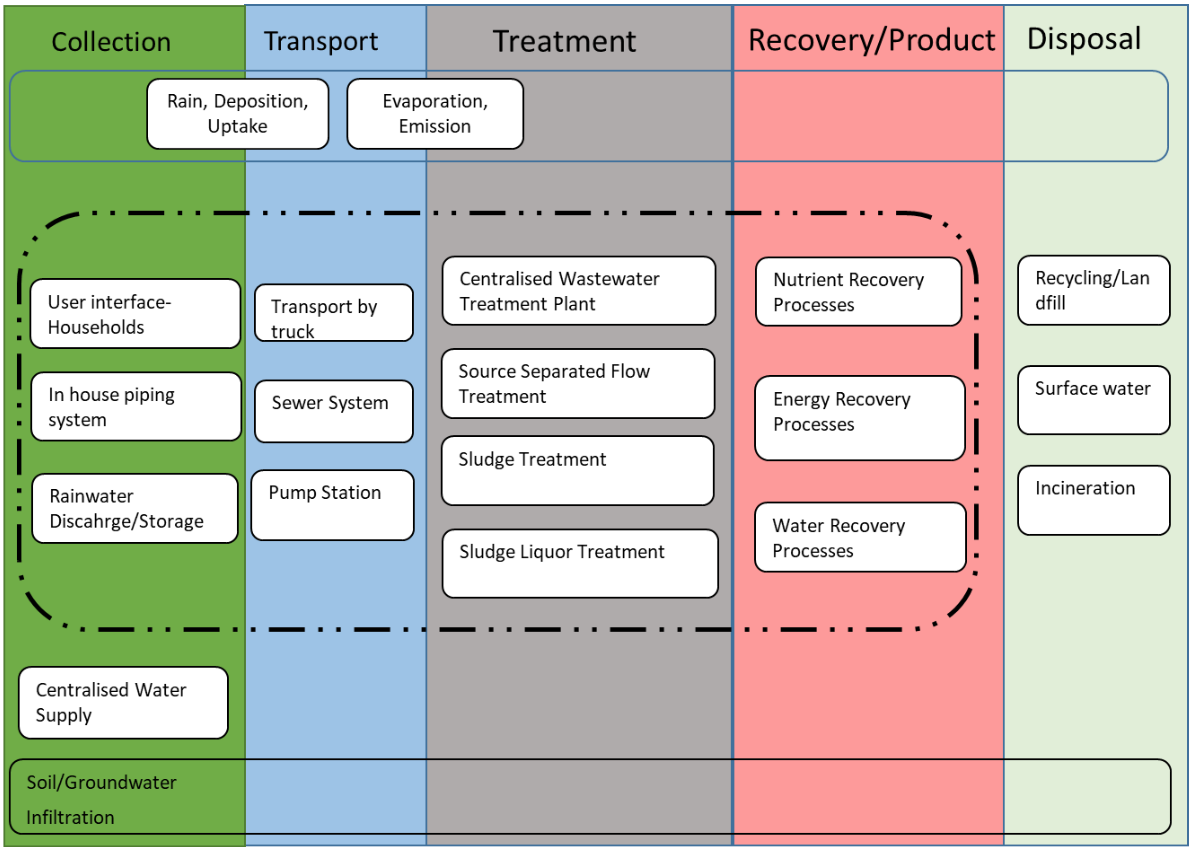

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Figure 7: Overview of the possible processes in the defined boundary condition based on functional group

3.4 Description of selected scenarios for modelling of concepts

3.4.1 Overview of selected scenarios

A scenario-based method is carried out for the evaluation of the developed model. The selection of scenarios is based on the maximum energy and nutrient recovery from the whole process. The scenarios include different routes for optimizing conventional and source-separated sanitation through different configurations of processes and source-separated flow.

The conventional sanitation concept focuses on the minimum changes in the infrastructure and recovered energy and nutrient with new configuration in each process. In source separation, the focus is on a highly concentrated flow for recovery. The scenarios of source separation are conceptualized based on the collection and treatment of various flows. An overview of the scenarios is delivered in Table 3. A brief description of each scenario is presented in the following chapter, whereas the process data can be found in chapter 4.

Since nutrient recovery efficiency is more significant on a larger scale, and the source separation concept is mainly implemented in the pilot plant scale, upscaling is considered for hypothetical source-separated scenarios to have a similar comparison base with conventional scenarios.

Wastewater treatment plant Berlin Wassmannsdorf is selected as a reference system with a treatment capacity of one million inhabitants. This plant reflects the current conventional sanitation system. Although this treatment plant is a conventional wastewater treatment for mixed wastewater, this plant is selected due to the existence of most of the required units for energy recovery (CHP plant) and nutrient recovery (Phosphorus precipitation).

Table 3: Description of different scenarios in this study

Abbreviation	Scenario type	Scenario target	Description
R0	Current situation	Reference	The existing situation of Waßmannsdorf
R1	Sludge liquor treatment	Annamox, denitrification	Energy-saving by separated treatment of high concentrated liquor
R2	Optimisation of sludge quality	Hydrolysis	Improving biogas production
R3		Enhancement of primary sludge production	
R4	Optimisation of disposal route	Mono-incineration	Energy production from incineration and decreasing harmful residual
R5	Optimisation for nutrient recovery	P-recovery by acid leaching	Substitute for mineral fertiliser and recover P
R6		P-recovery from ash	
S1	Separation of greywater	Energy and nutrient recovery from concentrated flow	Avoiding dilution of wastewater
S2	Separation of urine	Nutrient recovery from urine, energy recovery from BW+GW	Avoiding the pollution of urine and using gravity drainage to avoid the required cost for vacuum drainage
S3	Separation of blackwater, urine, and greywater	Maximize nutrient and energy recovery	Assessing the high potential of source separation concept

3.4.2 Current situation of conventional sanitation system-Reference scenario-R0

This alternative reflects the current conventional sanitation system regarding mixed wastewater. As shown in figure 8, inhabitants use a regular flush toilet. The other wastewater flows from households (bathroom, kitchen,...) is collected in a mixed sewer system and discharged to centralized wastewater treatment by a gravity sewer system.

Wastewater is treated in an activated sludge process, and sludge is anaerobically digested, dewatered, and dried. Biogas from anaerobic digestion is combusted in a CHP plant to produce heat and electricity. The excess sludge liquor is recycled back to the activated sludge. The dried sludge is incinerated in a municipal waste incineration plant, and the residual ash is disposed of in a landfill. A part of the dewatered sludge (16% of Dry matter) is transported to the mono-incineration plant in Berlin-Ruhleben. The rest is transported to a different lignite power plant for co-incineration. 28% of dried sludge is transported to the cement plant, and the rest is transported to a lignite power plant. This route distribution is considered in R0 as a reference scenario.

Biowaste from the kitchen and rainwater is neutral in this study. Even though both have effects on the resource recovery (biowaste for biogas production, rainwater for water harvesting) but referring to the result of prior studies and the European Waste Catalogue (the European Commission 2014) (Schüch et al. 2016)[3] not mixing biowaste with sludge digestion, biowaste is treated in a separated and is not considered in the evaluation process.

Precipitation of Phosphors is done after digestion and before the dewatering process to prevent uncontrolled precipitation of Phosphors in valves and pumps. Although the by-product can be utilised as a fertiliser, this wastewater treatment plant mainly protects the piping system from blocking uncontrolled precipitation.

[3] “This article tries to discuss all kind of organic waste but is focused on the bio-waste from private households that is collected by using bio-waste bins. Wastes collected through bio-waste bins, especially food, kitchen and yard waste, are monitored according to the European Waste Catalogue (The European Commission 2014.) laid down in the Commission Decision 94/3/EC and the German waste index regulation (AVV) under the waste classification key 200308 (biodegradable kitchen and canteen waste, with animal residues) (Deutsche Bundesregierung 2001).”

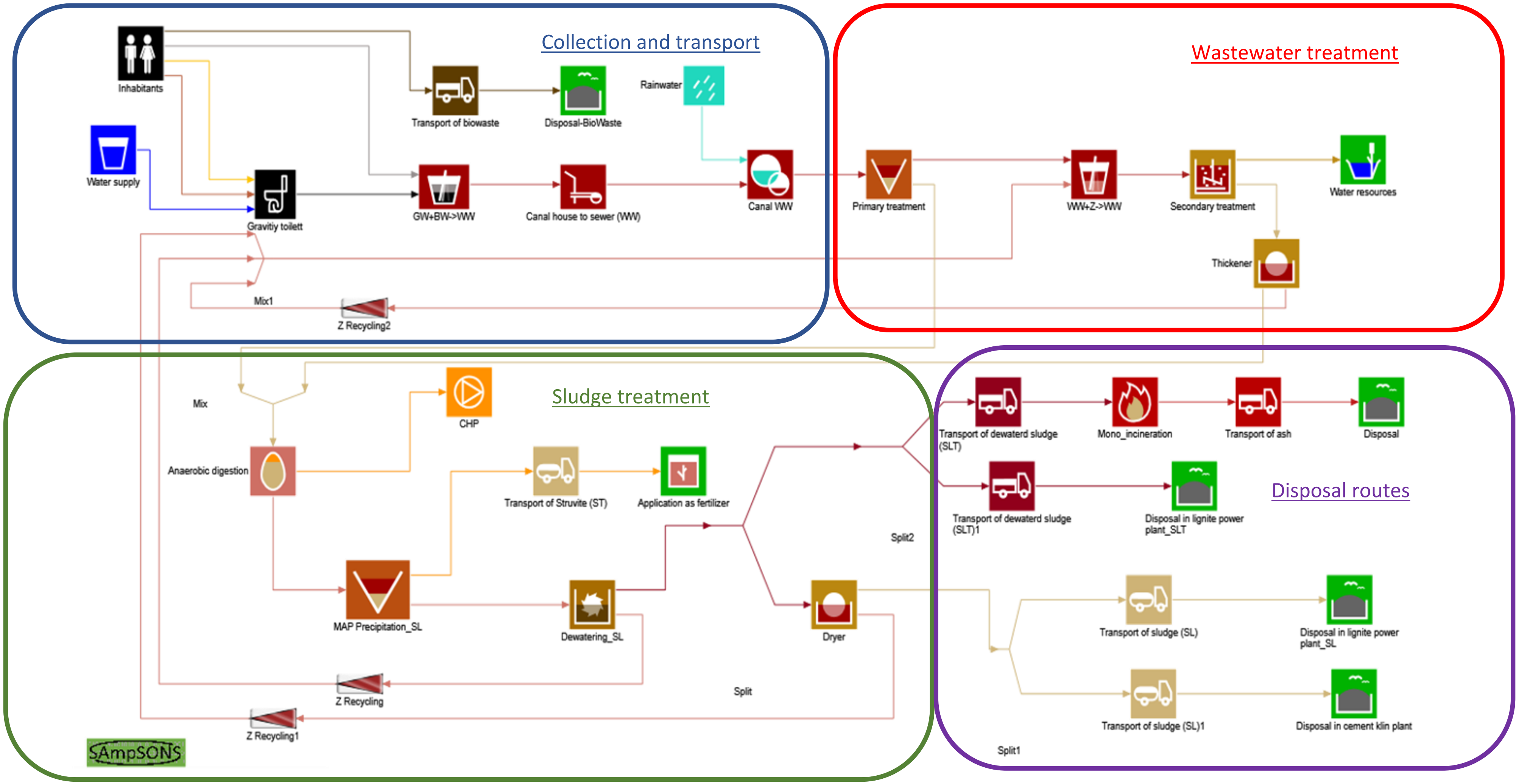

Figure 8: Schematic of scenario R0- Reference scenario

3.4.3 Optimisation of wastewater treatment- Sludge liquor scenario (R1)

This scenario includes all processes of conventional sanitation systems like reference scenario, R0 within additional setup for sludge liquor treatment (Figure 9).

Sludge liquor from dewatering and sludge drying is highly loaded with nitrogen and organic matter, causing an extra load to the wastewater treatment process in terms of energy demand and operation for pumping and aeration. The extra load can be decreased by a deammonification process for treating sludge liquor using an anaerobic ammonium oxidation process (Anammox) (Beier et al., 2008).

3.4.4 Optimisation in sludge treatment by hydrolysis (R2) and enhancement of primary sludge (R3)

- Sludge pre-treatment by hydrolysis- R2

This scenario includes all processes of conventional sanitation systems like scenario R1 within an additional setup for sludge pre-treatment by hydrolysis (Figure 10).

Due to the large fraction of microbial compounds in excess sludge, organic matter is only partly degradable in the digestion process. Pre-treatment of excess sludge by hydrolysis can improve the degradability of organic matter.

Different thermal, chemical and biological methods can hydrolyze organic matter (Remy 2012b). This scenario is based on the result of pilot trials in Braunschweig by thermal hydrolysis of excess sludge by steam injection due to the access to data. Excess sludge is preheated before steam is added to the sludge, reaching a temperature of 160°C and a pressure of 5 bar for 30 minutes. After hydrolysis, sludge is depressurized, and excess heat is recovered for sludge preheating. According to the pilot results, the relative increase of biogas is +10% (Work package 3 of CoDiGreen project).

Although hydrolysis improves the degradation of organic matter for increasing biogas production, at the same time, the other effect of thermal hydrolysis is the increase of the dissolved fraction of nitrogen and refractory organic carbon, which is recycled to the inlet of the wastewater treatment plant. Hence, the scenario of hydrolysis includes a process for sludge liquor treatment with a coagulation stage for the removal of organic carbon and a deammonification stage for the removal of nitrogen

- Enhancement of primary sludge production - R3

Since the primary sludge has more potential for biogas production than excess sludge due to the degradability of organic matter, this scenario is dedicated to the processes with the extraction of carbon-rich primary sludge before the biological step to recover energy as biogas. This process is called advanced primary treatment in this study (Figure 11).

The extraction of organic matter process is adopted from micro-screen filtration before biological treatment in POWERSTEP (Olsson und Pellicer 2018). Since the extraction of organic matter can lead to a different COD/N ratio which might cause to malfunction of the nitrogen removal, therefore this step is equipped with advanced process control in order to control the functionality of biological treatment and apply proper strategy including aeration, dosing coagulant and polymer (Database adopted from POWERSTEP project, Schubert 2018).

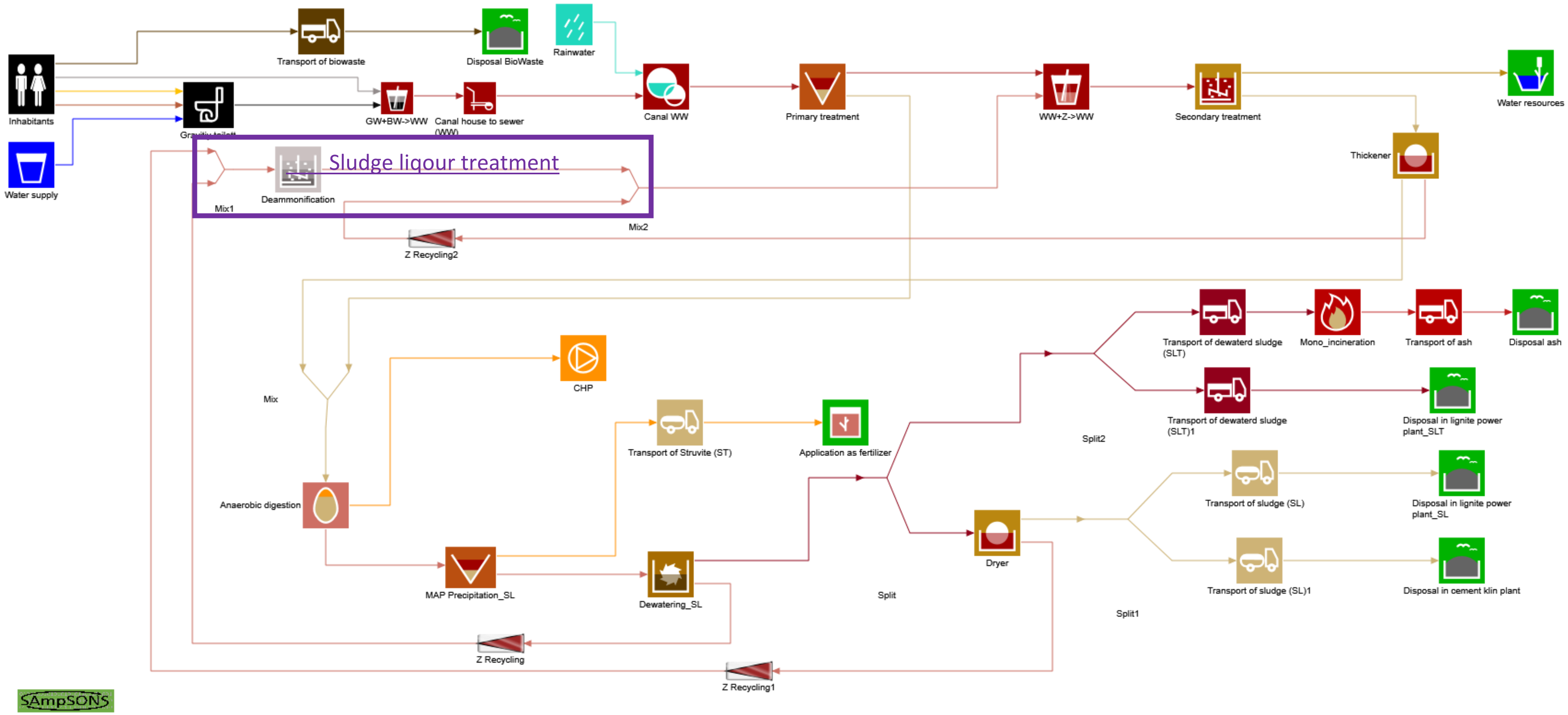

Figure 9: Schematic of scenario R1- Sludge liquor treatment

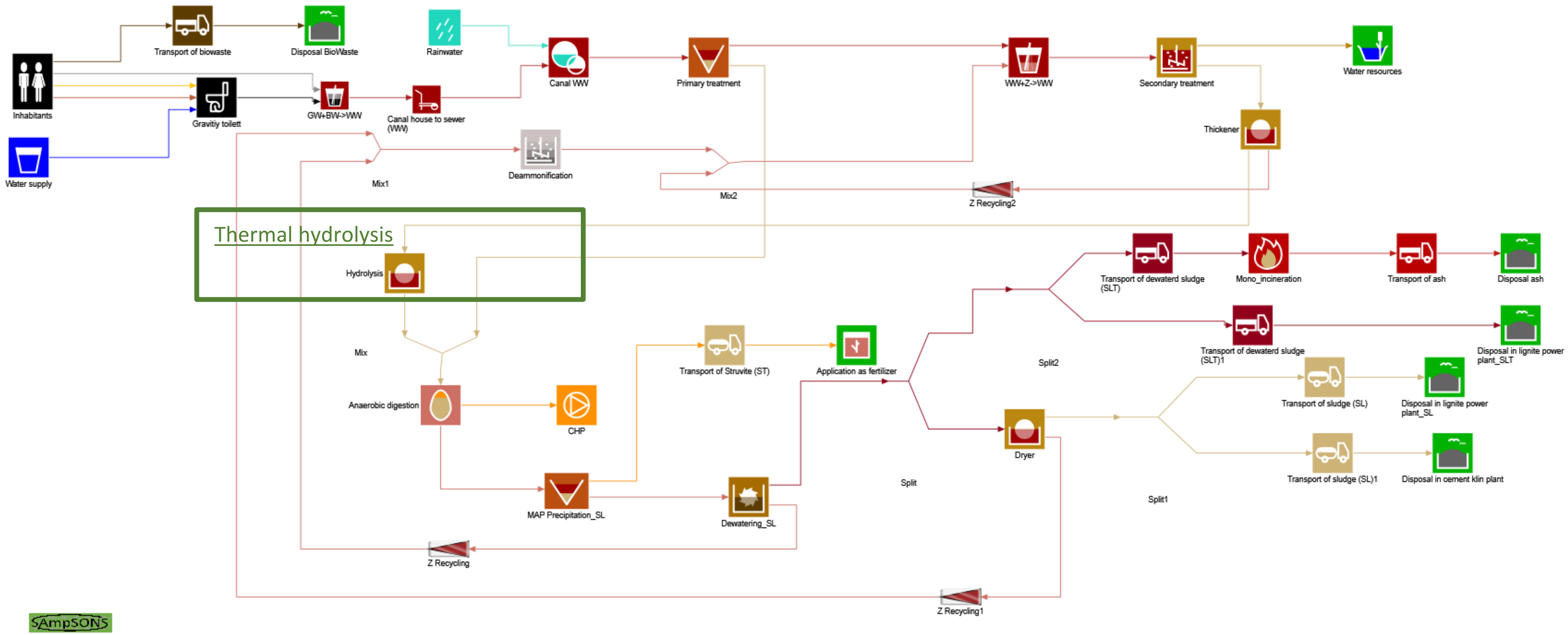

Figure 10: Schematic of scenario R2- Sludge pre-treatment by hydrolysis

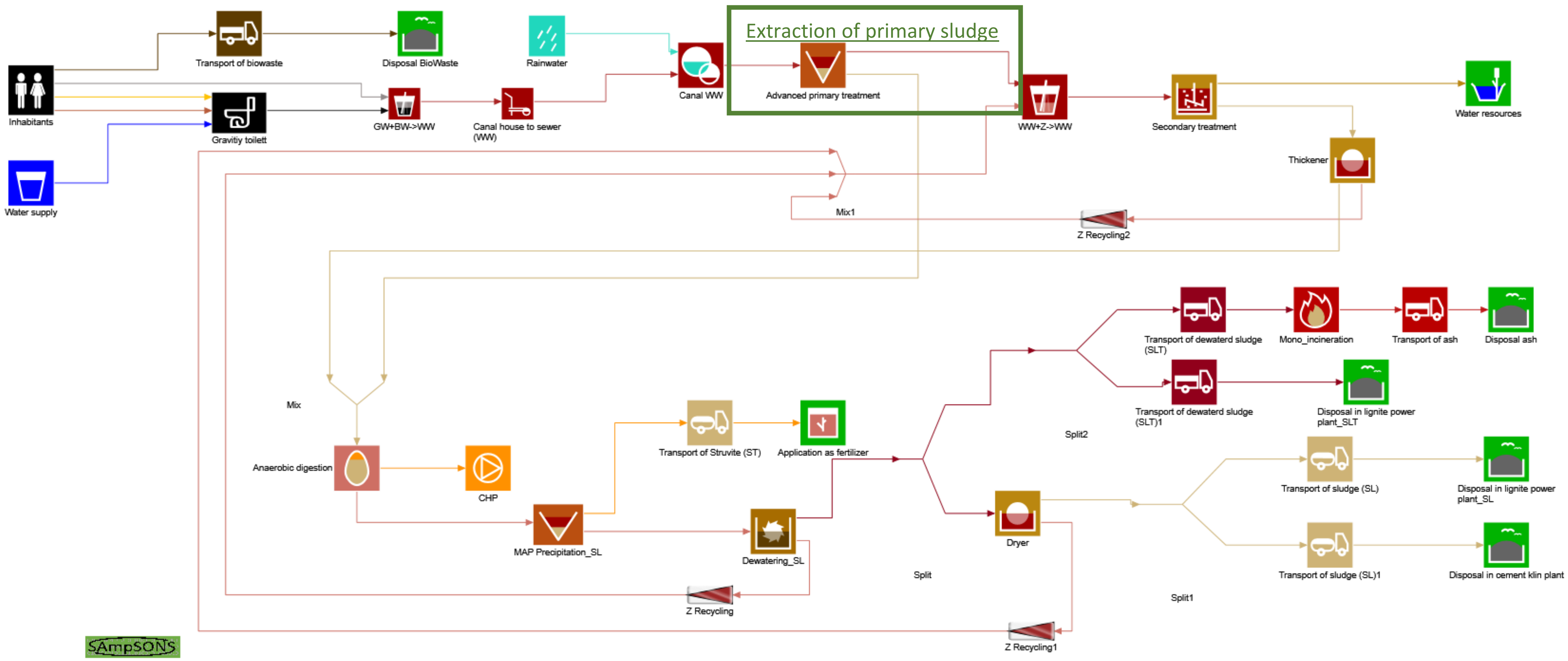

Figure 11: Schematic of scenario R3- Enhancement of primary sludge production

3.4.5 Optimisation of sludge disposal route- Mono-incineration-R4

In order to evaluate the effect of incineration processes on energy recovery, it is assumed that 100% of the sludge is disposed of using the respective disposal route.

Since in Germany, the installation of co-incineration is limited according to sludge legislation (AbfKlärV 2017) due to the negative effect of remaining heavy metal and fly ash (Wiechmann et al. 2013), the disposal route of co-incineration is not considered in scenarios.

As shown in figure 12, in scenario R4, the total amount of sludge goes to the mono-incineration plant. A part of sludge is dried (30%) and transported to an incineration plant, and the rest is transported directly for incineration. The drying process is increased the heating value of the dry matter, but it is a high energy-intensive process (Remy, 2015). The reason for choosing 30% of the drying process is to have the results based on the reference scenario and investigate the effect of mono-incineration compared to the reference scenario.

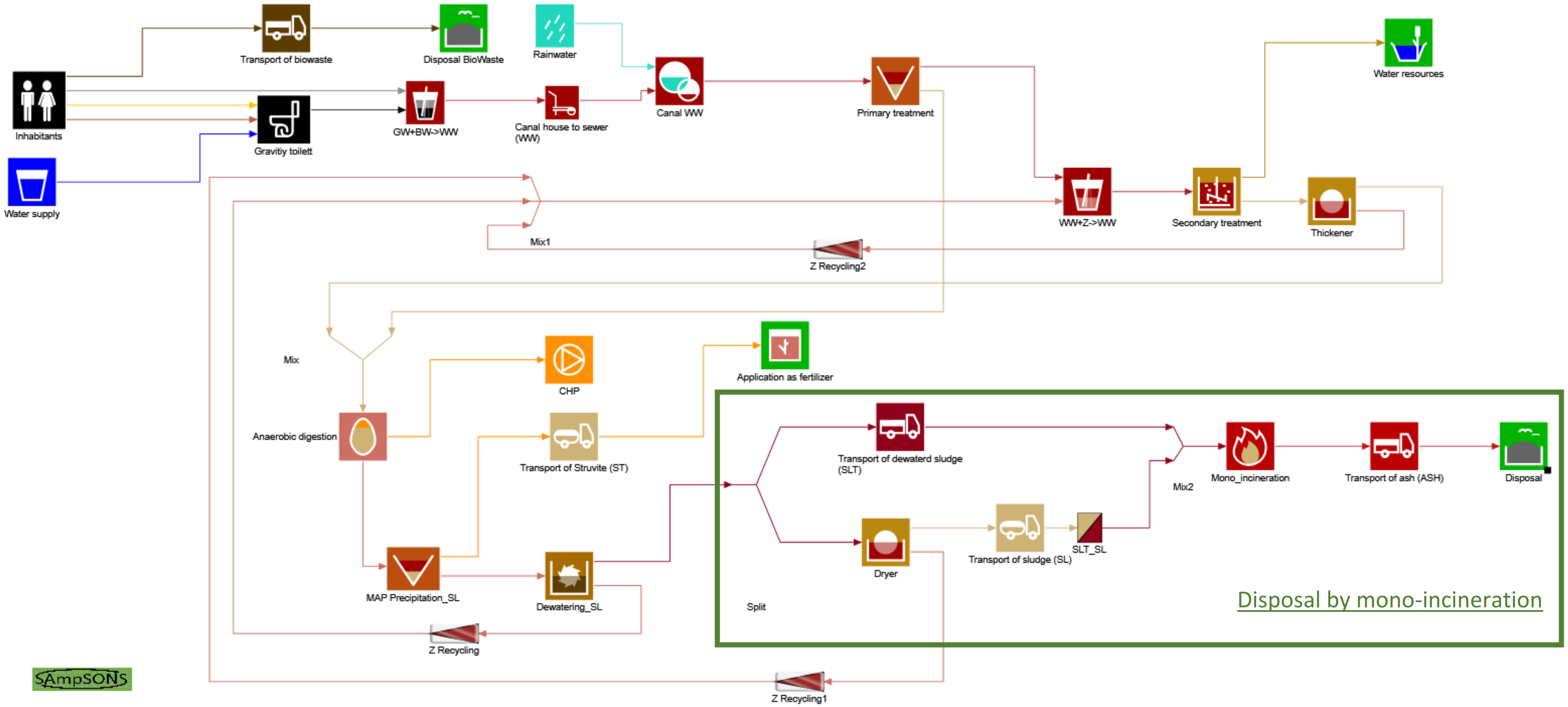

Figure 12: Schematic of scenario R4- Disposal route by mono-incineration

3.4.6 Optimisation of nutrient recovery by acid leaching in sludge liquor (R5) and recovery from ash (R6)

- P recovery from sludge liquor by acid leaching- R5

This scenario optimises phosphor recovery from sludge liquor by acid leaching (Figure 13). The concept of this process is adapted from Gifhorn (Hermanussen et al.2012). Digested sludge is directly acidified in digester in a proper hydraulic retention time (1 Hour) which causes the bounded phosphor in sludge to transform into dissolved PO_4-P. The side effect of this process is the mobilization of the other existing metal in sludge which should be prevented to transfer to the final phosphor by-product and appropriately separated. The separation of solid and liquid phases is done in the MAP reactor with polymer and precipitant dosing.

- P recovery from ash-R6

This scenario is developed based on acidic leaching of mono-incineration ash developed by BSH Umweltservice GmbH (Remy 2015) (Figure 14). The highly loaded liquid is treated by adding precipitants (NaOH and lime slurry). The addition of dilute acid to the ash causes the phosphorus to dissolve. The Solids are separated in a filtration plant, and the residues are disposed of. The by-product is a mixture of Al, Fe, and Ca-phosphate, which must be treated further to separate the remaining heavy metals.

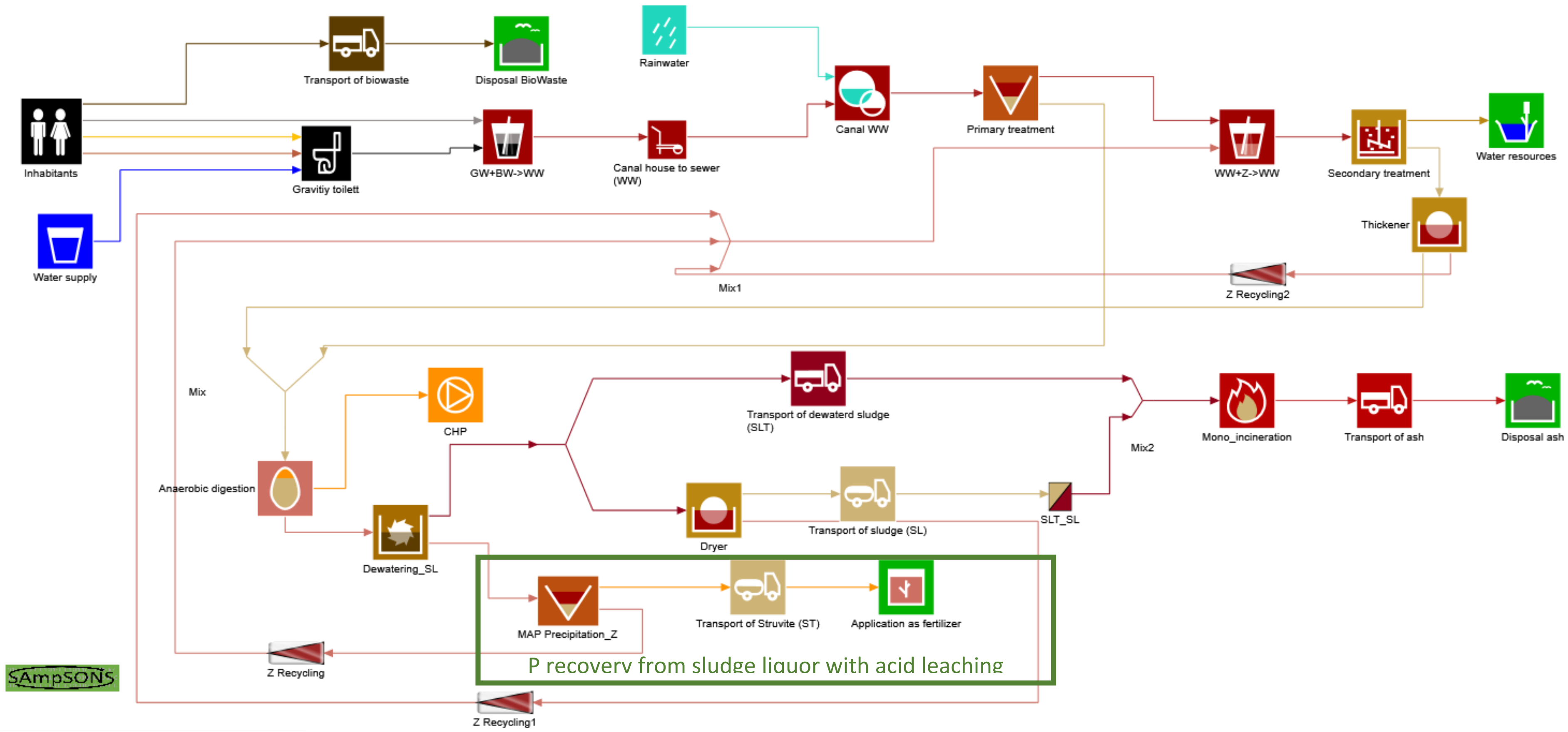

Figure 13: Schematic of scenario R5 - P recovery from sludge liquor by acid leaching

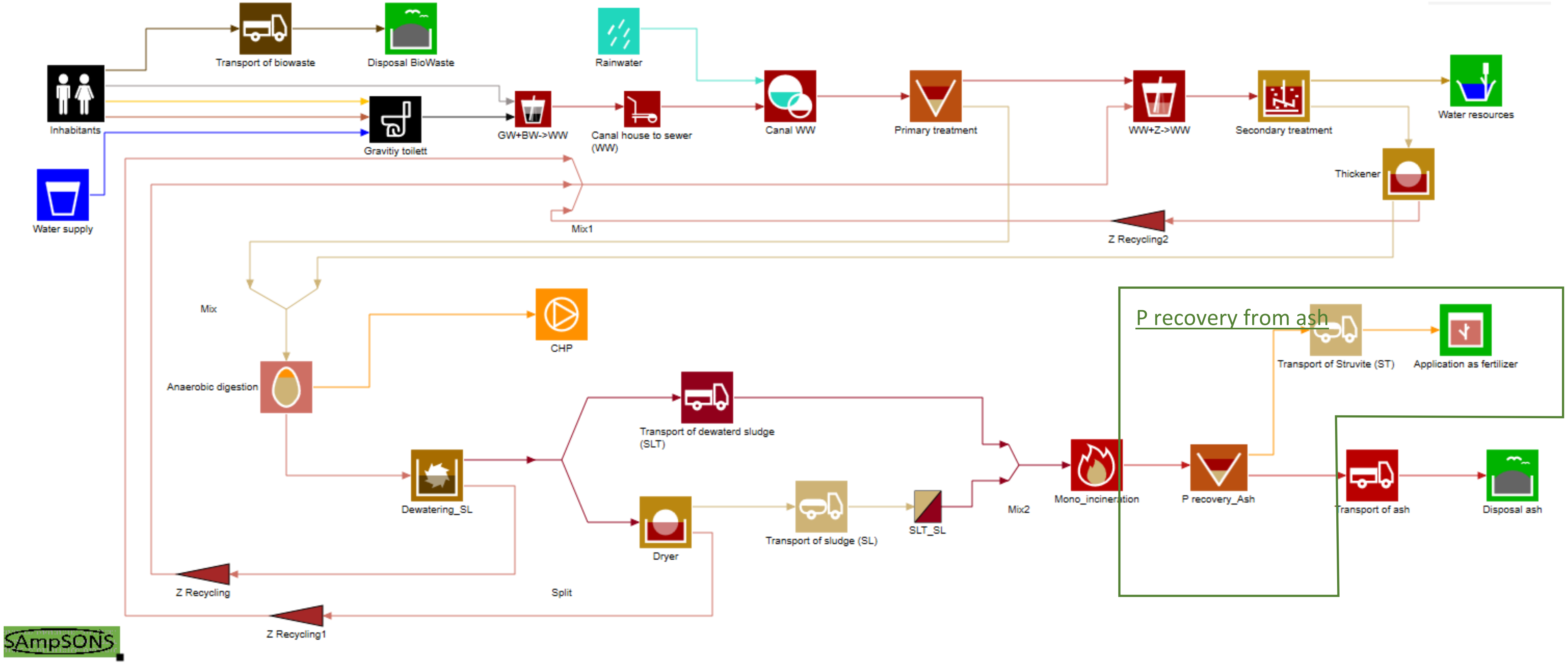

Figure 14: Schematic of scenario R6 - P recovery from ash

3.4.7 Scenarios for optimisation by an alternative sanitation system

- Separation of greywater-S1

Greywater is collected in the gravity sewer system and directed at a centralized activated sludge process for treatment. This process is selected to be comparable with the reference scenario. A load of activated sludge is affected by only greywater (Figure 15).

The separated piping system in source separation is considered to reflect the required sewer length and related constructional effort. Detailed information is given in sections 5-2 and 5-3 for piping in building and sewer systems.

In order to take advantage of anaerobic digestion of blackwater to maximize the biogas production, blackwater is collected by vacuum toilet and less flush water and transported with vacuum sewer system to the digester.

The main focus of nutrient recovery is phosphorus, which is mainly accumulated in sludge—the recovery processes located in two different points of this scenario. The first location is after digestion, which is based on a reference scenario to control phosphorus precipitation to avoid clogging. After mono-incineration, the maximum recovery is happening by acid leaching to produce plant-available fertiliser.

Since nitrogen recovery is an intensive energy demand process and the product is not economical compared to industrial products, there is no legislation to recover; the concentrate after P recovery returns to activated sludge for removal by nitrification /denitrification.

- Separation of urine-S2

Urine separation is done to maximize the nutrient recovery with less volume than scenario S1. Therefore the possibility of nitrogen recovery, which is the energy-intensive process of stripping, is applicable (Figure 16). The application of a urine diversion toilet and a separated piping system for urine collection from buildings is considered. The undiluted urine is stored in the neighbourhood of apartment buildings and transported to a nutrient recovery plant, whereby P and N are recovered as struvite by a precipitation process. The rest of the existing nitrogen is recovered by steam stripping to produce an ammonia solution as a fertiliser. The remaining flow, which contains high concentrated micro-pollutant, is directed to disposal. The flow, including greywater and blackwater, is discharged to the activated sludge and anaerobic digestion for biogas production and P recovery process after digester to recover existing phosphorous in this wastewater line.

Although nitrogen recovery is not considered in recovery from wastewater due to intensive energy demand to recover from high diluted wastewater, steam stripping is used in this scenario for high concentrated separated urine to study the effect of nitrogen recovery against nitrogen removal.

- Separation of blackwater, urine, and greywater-S3

This scenario is based on the separation of all the wastewater fractions to observe the function of each flow at the maximum level. A urine diversion toilet is considered to collect separate urine and faeces. Three separated piping systems are collecting and transferring flows. Urine is treated in the same way as the S2 scenario by phosphorus precipitation and steam stripping for nitrogen recovery. Greywater is treated similarly to S1scenario by an activated sludge treatment process. Blackwater is directed to the digester to produce biogas. Existing phosphorus in residual concentrate is precipitated before returning concentrate to activated sludge process, which is used to treat greywater flow (Figure 17). This step avoids uncontrolled phosphorus precipitation avoids clogging. The digested sludge produced from separate greywater treatment and blackwater is directed to the mono-incineration unit. Then phosphorus recovery from ash is considered the core nutrient recovery process in this scenario.

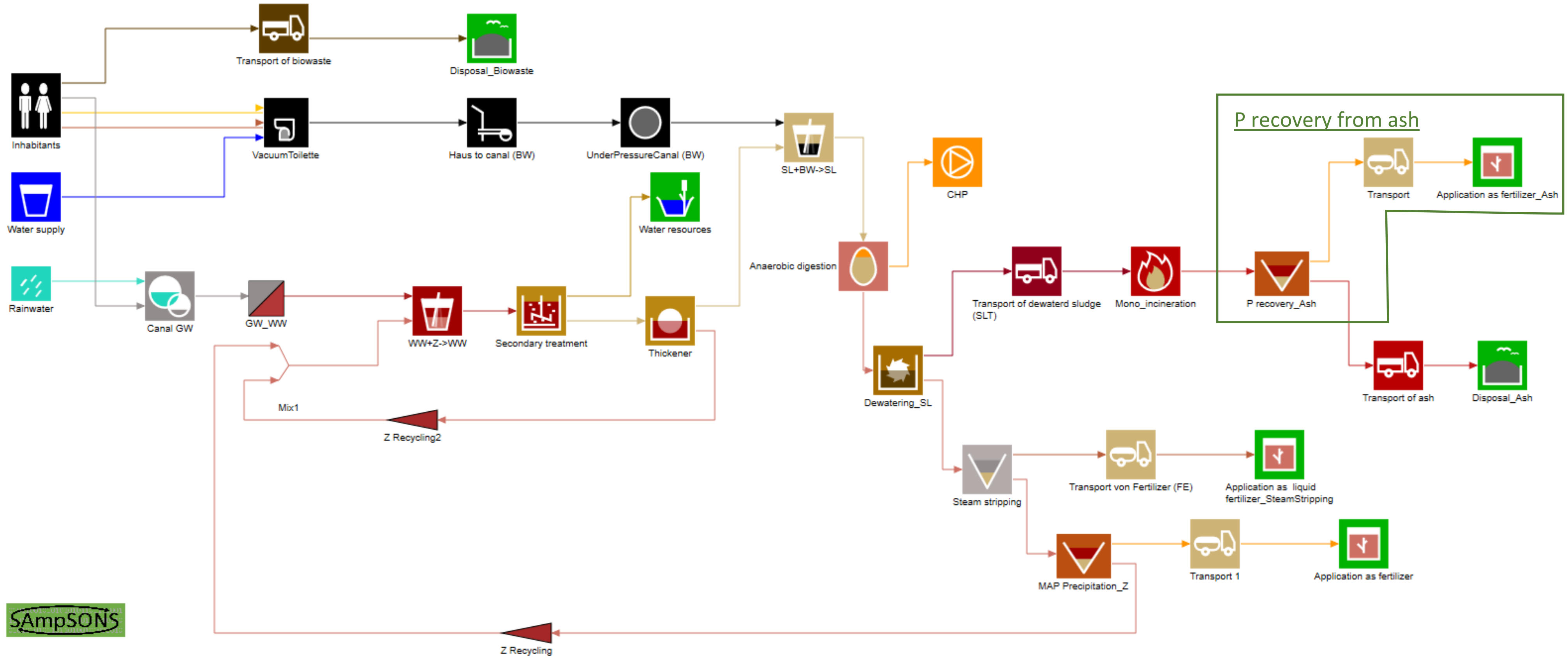

Figure 15: Schematic of scenario S1- Separation of greywater

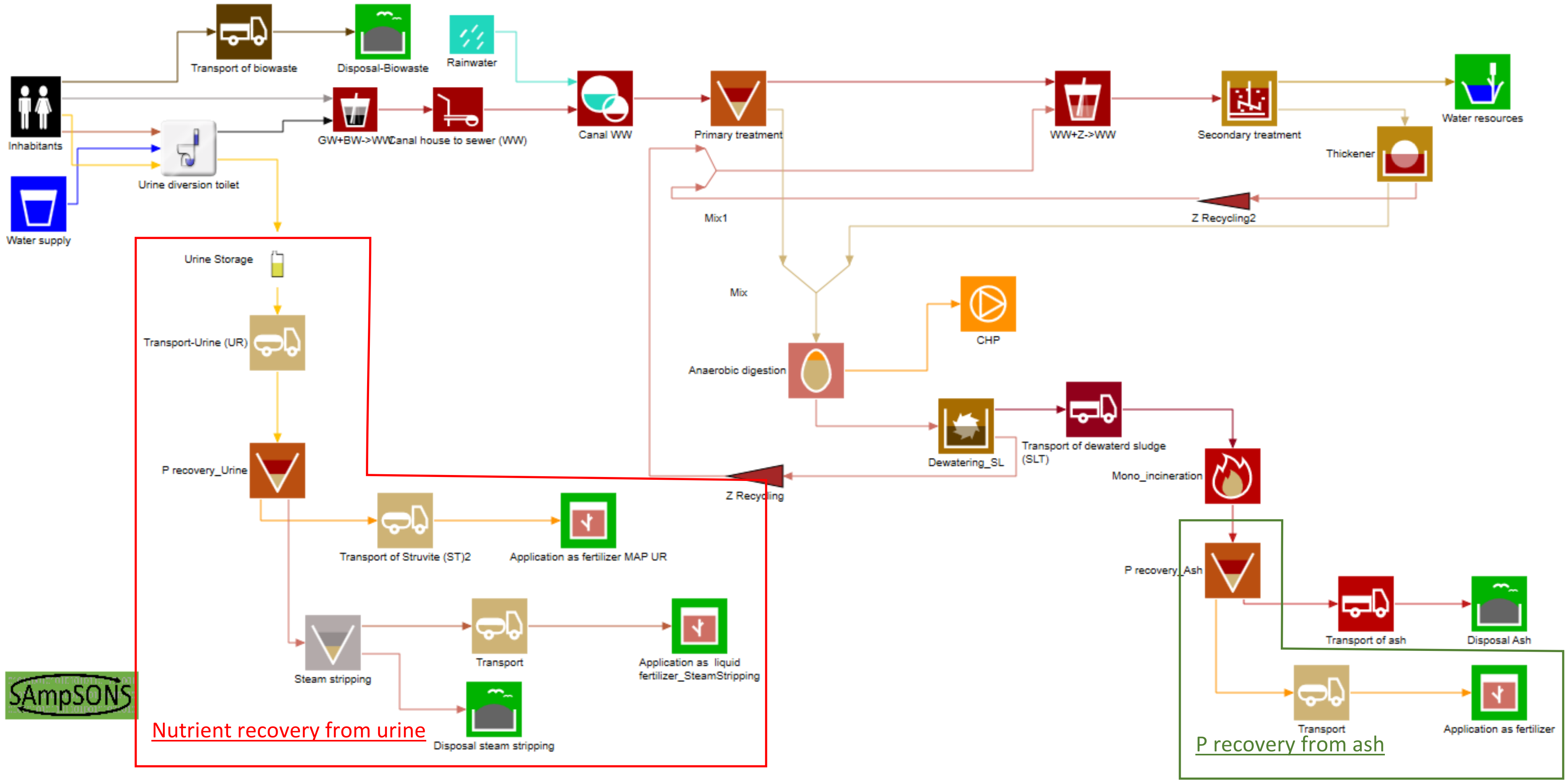

Figure 16: Schematic of scenario S2 - Separation of urine

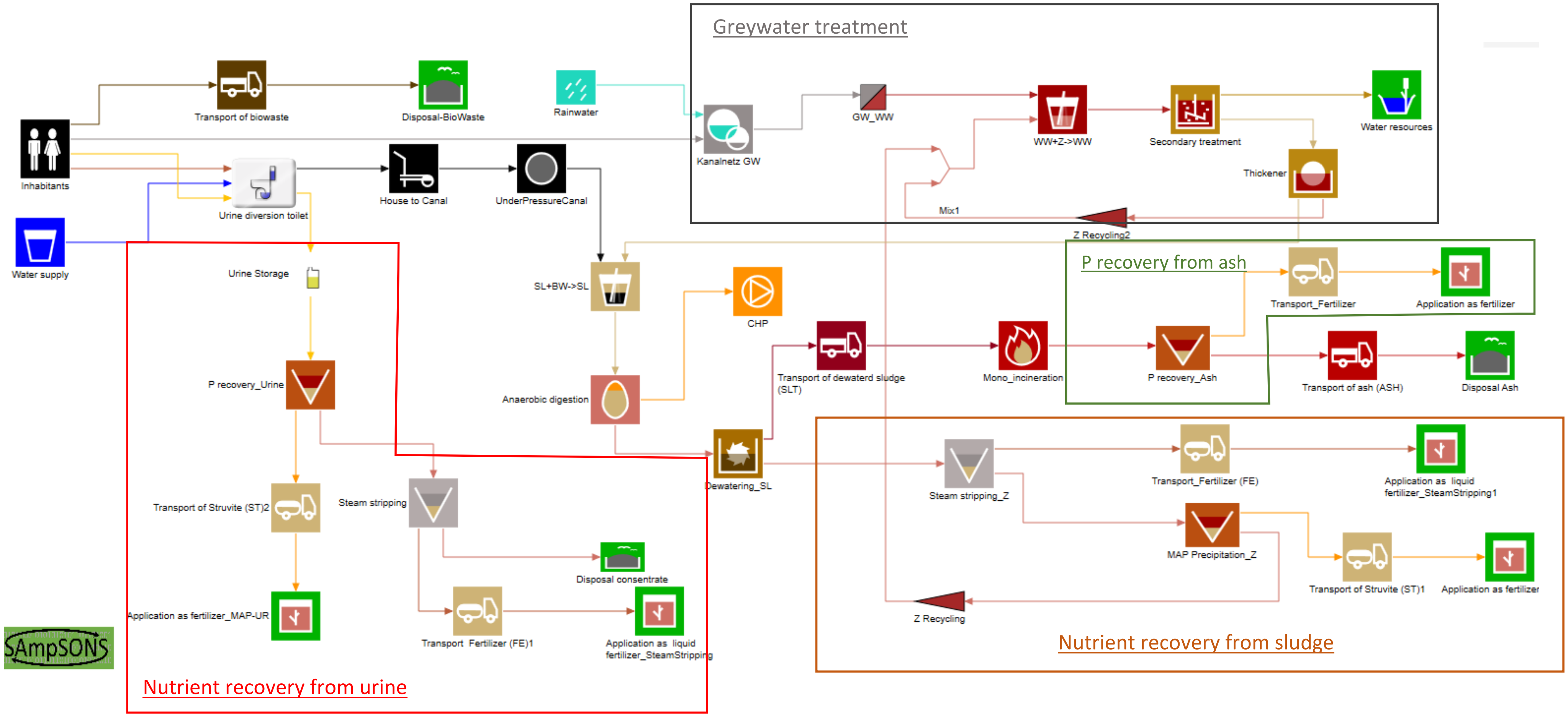

Figure 17: Schematic of scenario S3 - Separation of blackwater, urine, and greywater

3.5 Specification of sustainability assessment method

3.5.1 Dimensions of sustainability in the sanitation system

Prospective sustainability analysis of the urban sanitation system includes ecological, economic, technical, and social aspects. Since the evaluation of sustainability requires the index parameter for each aspect, the classification is done based on ecological, economic, technical, and social. The method for choosing indicators are adopted from the TWIST++ project, where indicators are carefully investigated for different sizes of wastewater treatment in Germany (Sartorius et al. 2016a; Sartorius et al. 2016b). The grouping of the selected indicators reveals the significant effect on evaluating different concepts in terms of sustainability. However, there is a slight modification for the selected criteria due to different investigated processes.

According to the goal-setting of the TWIST++ project, safety is considered a vital aspect for assessing microbial indicators. However, microbial assessment is beyond the study's goal in the current study. The main focus is on resource recovery; therefore, the microbial assessment is not considered, and safety is assessed as an indicator of the social aspect. Figure 18 shows the selected sustainability aspects in this study. This classification underlines the multi-criteria aspect of the sanitation system.

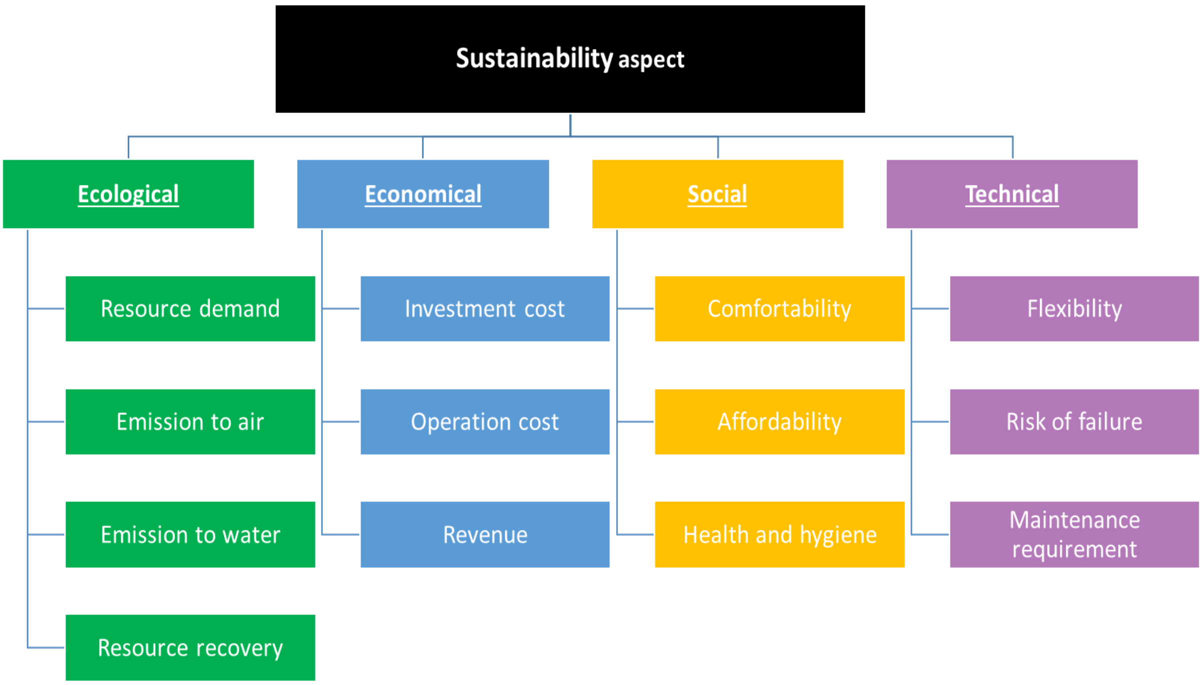

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Figure 18: Assessment of sustainability for the sanitation system

3.5.2 Weighting and scoring of sustainability indicators

The review of relevant literature in the field of sustainability assessment for sanitation system (Hügel 2003; Balkema et al. 2002; Rosemarin 2008; Remy 2015; Guest et al. 2009; Trimmer 2016; Sartorius et al. 2016; Andersson et al. 2016; Garrote et al. 2019) shows up to 35 different criteria for evaluation of these aspects. It leads to the complexity of a conclusive answer for comparing conventional and source separation concepts. Therefore, this study developed a practical method for choosing indicators, weighting, and scoring for a multi-criteria analysis.

Scoring index and weighting have been done by Lindholm, Greatorex, and Paruch (2007) method who studied sustainability indicators for alternative urban infrastructures systems.

According to the selected sustainability aspect, 29 indicators is contributed to the weighting and scoring system. Table 4 shows the selected indicators and the related weighting for each indicator. The weighting of sustainability indicator is done based on the structured system study in TWIST++ project. Due to slight changes in the selected indicators, the modification was carried out based on the goal of this study.

The weighting of criteria performed by dividing all selected criteria to 100%; shows the contribution of 22% technical, 25% ecological, 15% economic, and 38% social in sustainability assessment. This contribution is divided between the selected indicators to show the involvement of each indicator in the scoring system.

Scoring is done by grading each (sub)indicator on a scale of 1-5, where one is the lowest and five is the highest. The scoring scale for each indicator is chosen based on the mean and standard deviation of the range of values from different scenarios. The overview of the scoring system is shown in Table 5, and detailed scoring scales for different dimensions are shown in Annex A.1.

The scoring was carried out for every 29 indicators to define the effect of each indicator in the whole system.

Table 4: Indicators for the ecological dimension of sustainability

Sustainability aspect	Criteria	Indicator	Sub-Indicator	Type of indicator	Weighting %
Ecology					**25**
	Emission to air	Global Warming Potential	CO_2	Quantities	0.7
			N_2O		1.2
			CH_4		0.9
			NH_3		0.7
			SO_2		0.7
	Emission to water	Eutrophication Potential	COD, P, N		3
		Acidification Potential	NH_3, NO_x, SO_2		0.5
		Nutrient load	N (N_{total}, NH_4-N)		0.6
	Resource demand	Cumulative Energy Demand	Electricity/thermal		3.9
		Material demand	Chemical supply		1.8
	Resource recovery	Water supply saving			2.5
		Recovered N			0.8
		Recovered P			2.5
		Recovered electricity			3.5
		Recovered heat			1.7
Economic					**15**
	Investment cost				5
	Operation and maintenance				8
	Revenue				2
Social					**38**
	Comfortability	Complexity		Qualitative	6
		Oder			5
		Nuisance			2
	Affordability	Extra cost			7
	Health and hygiene	Risk for microbial infection			18
Technical					**22**
	Flexibility/expandability	Potential for optimisation		Qualitative	6
	Risk of failure	Failure risk			6
		Capacity of reserve			2
		Knowhow level			3
	Maintenance requirement				5

Source: Adopted and modified from TWIST++ project

Table 5: Overview of scoring system for each sub-indicator

Sub-indicator	Grade	Score
Range of value based on average and standard deviation	Very high	5
	High	4
	Moderate	3
	Low	2
	Very low	1

3.5.3 Classification and characterization of sustainability

The ecological aspect has been investigated with Life Cycle Assessment (LCA) (Remy und Ruhland 2006). Cumulative energy demand (CED) represents the direct and indirect energy use and production which correlates to the number of fossil fuels that are consumed for a particular process (DIN-VDI4600, 2015, IINAS 2019). This indicator determines many products and services, thus making it practical to measure the total energy demand of various processes.

Global warming potential (GWP) indicator quantifies the contribution of greenhouse gases based on main contributors, CO_2, N_2O, and CH_4, to the global warming phenomenon. The characterization factor is based on the Intergovernmental Panel on Climate Change (IPCC 2006) 's developed a model for a 100-year time horizon and CO_2 as a reference substance. CO_2 emissions from renewable fuel (e.g., from biogas combustion) are considered biogenic substances and are not accounted for in this indicator.

The acidification potential (AP) is related to the acidifying air pollutants (NH_3, NO_x, and SO_2). It is accounted based on SO_2 as a reference substance with a dispersion model for long-range transmission of air pollutants in Europe (EMEP) European Monitoring and Evaluation Programme) and the acidification model RAINS-LCA (Remy, 2010, M.A.J. Huijbregts et al. 2016).

The eutrophication potential (EP) defines the eutrophication of aquatic and terrestrial ecosystems by the emission of NH_3 and NO_x. It is calculated based on the RAINS-LCA model (Remy, 2010, Huijbregts, 2016), and PO_4 is considered a reference substance for the characterization factor. Table 6 shows the selected indicator for each parameter.

Emissions and extraction are characterized based on Life Cycle Inventory which describes the respective environmental impact concerning a fixed reference. Consequently, a category's impact is aggregated to one indicator scale with a mutual unit.

The calculation of characterization is based on a specific scientific method for the different indicators (Remy, 2010) and is presented in the LCI database (GABI, Eco-Invent). These factors for the impact assessment are listed for each indicator in Annex A.2.

The economic aspect as one of the critical aspects of sustainability is assessed with the concept of cost-effectiveness analysis developed by Meinzinger (2010). In principal capital, operation and disposal, and revenue based on the related life span included in a cost analysis.

Table 6: Indicators for the ecological dimension of sustainability

Impact category	Acronym	Selected indicator	unit	Source
Non-renewable cumulative energy demand (fossil/nuclear)	CED fossil	Fossil fuels	MJ	VDI 4600 [1)]
Global Warming Potential	GWP	CO_2 (fossil), N_2O, CH_4	kg CO_2-eq	ReCiPe[2)]
Terrestrial Acidification Potential	TAP	SO_2, No_x, NH_3	kg SO_2-eq	ReCiPe[2)]
Fresh water Eutrophication Potential	EP_{fresh}	P emission in water and soil	kg p-eq	ReCiPe[2)]
Marine Eutrophication Potential	$EP_{seawater}$	N emission in air, water, and soil	kg N-eq	ReCiPe[2)]

1) VDI August 2015 – VDI 4600 BLATT 1 IINAS 2019 (to check for use this source) 2) Huijbregts et al., ReCiPe 2016

The social aspect of a sanitation system is another critical driver in the sustainability concept, and it expresses the impact of the behaviour of inhabitants in the sanitation system. The main barrier to considering the social aspect in the sustainability assessment is quantifying these impacts properly.

The scoring based on quantitative data mainly involving technical, environmental, and economic dimensions is more manageable to investigate than the qualitative social aspect.

Despite some studies have already tried to include the social aspect into sustainability assessment (Munn und Timmerman 2002; Jorgensen et al. 2008; Kloepffer 2008; Lienert und Larsen 2010, Bach 2017) and the released guideline by UNEP/SETAG to establish a framework for social LCAs (UNEP 2009), however, there is still a lack of quantitative relationships between the social indicator and process units. Often their meaning and relevance are suggested by local stakeholders (Cossio et al. 2020b).

Integration social aspect with primarily qualitative parameters with other aspects of sustainability is a complex process, and establishing a new method for evaluating these indicators is beyond the goal of this study. Hence, the social aspects are observed as the main driver for assessing sustainability. It is implemented in the tools in terms of acceptance and flexibility. The interpretation has been made based on the tool's output in the result section of this study.

3.6 Data collection structure and evaluation process

Since pilot projects have been implemented concerning source separation, sanitation is limited. Therefore, long-standing data are hardly available for different dimensions of the treatment plant, and generating data is beyond this study's goal; therefore, data from different literature reviews, technical reports are collected, and the quality check is done considering the quality and related capacity is applied.

The data collection and evaluation approach was developed based on a datasheet for each process unit. According to data availability, each datasheet contains the main feature of technical, ecological, economic, and social information.

The required data to build the database was extracted from technical and scientific literature and pilot plants. Therefore, both empirical and theoretical data were considered.

Data collection has been done based on the rating of data regarding relevant technical and variation parameter information in each process according to the geography, sampling method, and sampling techniques, and analytical methods were integrated into the data collection.

Various authors have published literature studies on the characteristics of source-separated wastewater concepts in the past. These are often based on a relatively small number of sources and do not contain corresponding values for all wastewater-relevant parameters, and do not focus on European data (Eriksson et al. 2002; Londong und Hartmann 2006; Halalsheh et al. 2008; Meinzinger und Oldenburg 2009; Hernández Leal et al. 2011; Thibodeau et al. 2014; Rose et al. 2015).

The data basis on the characteristics of source-separated flow (urine, black- and greywater) is still weak; the variation value is introduced from different works. Since this knowledge is fundamental for designing treatment units and assessing environmental impacts and the energy potential, a systematic collection and processing of source-separated flow (blackwater, greywater, and yellow water) database are done. The value for characterizing the source-separated flows are based on the overview of published data on volume flows, concentrations, and inhabitant-specific loads of each flow (DWA 2008; DWA, 2011; DWA-Neuartige Sanitärsysteme 2015) and the recent research which is carried out in the context of KREIS project by Sievers 2018 for greywater and Wätzel und Kraft 2014b for blackwater.

The representativeness, trustworthiness, and clarity of the source of collected data were crucial aspects of data analysis. The following aspects were therefore considered in the data collection process:

- Only parameters were recorded in the data collection, collected explicitly in the published studies, or derived from technical regulations. Publications that did not contain measurements from their research or reference to other sources were not included in the compilation

- The specification of references led to higher trustworthiness of the sources used since these references to the primary literature made it possible to verify the statements made

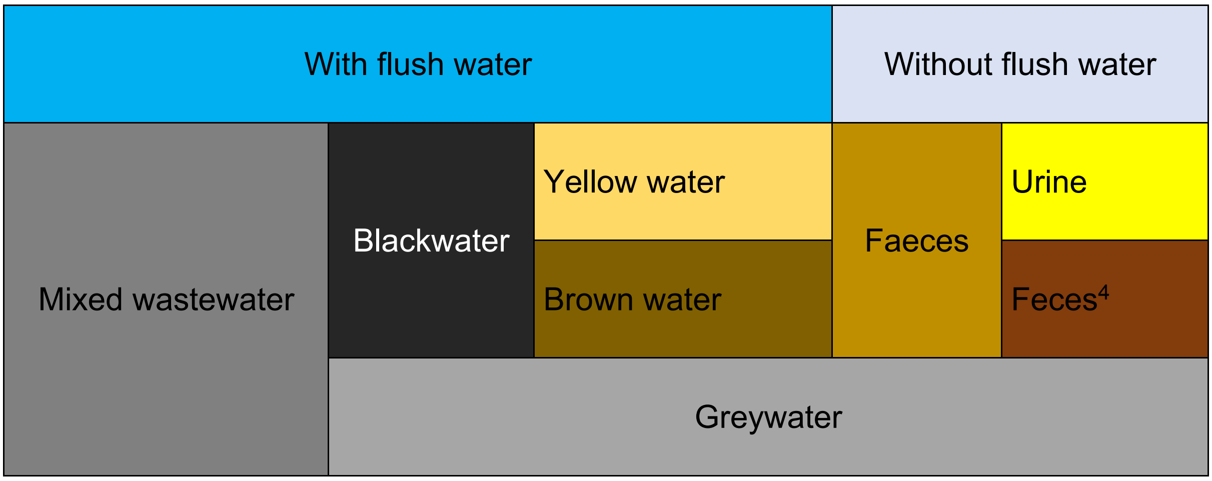
- Literature from academic sources often has a better theoretical foundation than technical reports. By contrast, technical reports are more suitable for identifying current trends and developments

3.7 Characteristic of flow in source-separated and conventional sanitation systems

3.7.1 Definition of flows in each sanitation concept

In the urban sanitation system, wastewater flow is the main element that can show the system's behaviour in different conditions. It becomes even more significant in source separation-based sanitation concept, where wastewater is separated according to their degree and type of pollution and potential of resource recovery (Kujawa-Roeleveld und Zeeman 2006). Generally, nutrients and energy can be recovered efficiently from the high concentrated flows, while the less concentrated flow allocates to water sources (Tervahauta et al., 2014).

Various configurations of source-separated wastewater have been defined in the literature, such as light greywater, dark greywater, blackwater (urine, faeces, and flush water and biowaste from kitchen and garden), yellow water, brown water. Blackwater can be further split into urine and faeces using urine-diverting toilets or urinals and can be investigated as yellow water (only urine and flush water), brown water (faeces, toilet paper, and flush water). The main classification of different wastewater flows is given in figure 19. Due to the various range of each flow, in the following section, there will be a brief explanation of substantial wastewater flows investigated in this study.



Source: Barjenbruch and Wriege-Bechtold, 2017

Figure 19: Classification of various wastewater flow

[4] Faeces is UK and feces US spelling and here to differentiate, feces is only solid part and with mix of urine is faeces

The range of each flow highly depends on the variety of nutrition and digestibility of the food (Meinzinger, 2010), the type and quantity of products applied in laundry, and personal care (Mujtaba et al., 2017). Regarding an extensive variety of value of flows, a fixed characteristic value of source-separated wastewater flow should be pursued in the context of this study.

Table 7 presents the main characteristics of each flow. This study uses the average value derived from a review done by the task group on new sanitation concepts for the German Water Association (DWA) (Meinzinger und Oldenburg 2009). The review involved more than 200 European references to derive an average value for each flow. Due to different sources of study and variable conditions, the sum of source-separated does not fit mixed wastewater. More detailed information on data processing is shown in Annex A.3.

Table 7: Average load of urine, faeces, greywater, and mixed wastewater

Parameter		Unit	Mixed wastewater *	Urine	Greywater	Faeces
Volume		lit/(pe.a)	150	1.37	82	0.14
Solid	**DM**	g/(pe.a)	70	57	71	38
	oDM	g/(pe.a)	-	41	44	35
Organic	**BOD**	g/(pe.a)	60	5	18	20
	COD	g/(pe.a)	120	10	47	60
Nutrient (inorganic)	**N**	g/(pe.a)	11	10.4	1.25	1.5
	P	g/(pe.a)	1.8	1	0.5	0.5
	K	g/(pe.a)		2.5	1	0.7
	S	g/(pe.a)		0.7	2.9	0.2

Source: See Annex A.3

*The sum is not fit due to different sources and studies for characterization of flows

Urine contains the most nutrients, and its isolation enables efficient recovery from a much smaller volume. Greywater is the most significant portion of domestic wastewater, is minimally contaminated, and therefore appropriate for reuse. The high content of organic matter in urine and faeces make it ideal for energy/nutrient recovery.

3.7.2 Blackwater

Blackwater is a mixture of faeces, urine, flushing water, and toilet paper. Toilet paper contributes to DM and COD and is not easily degraded because of its cellulose content (Larsen et al., 2013).

A large fraction of domestic wastewater's main components, including organic matter, nutrients (nitrogen, phosphorus, potassium), pathogens, pharmaceutical residues, and hormones, are present in a small volume of faeces and urine.

Almost 50% of the nitrogen in faeces is water-soluble, and 20% of this amount is ammonia which is biochemically degraded from urea and amino acids. The central portion of phosphorus in the faeces is found as undigested calcium phosphates. Potassium is mainly ionic (Zeeman und Lettinga 1999; Lindner 2007). Many different pathogens (bacteria, viruses, and parasites) are present in faeces. Faeces are the second, after urine, source of pharmaceuticals, hormones, metabolites excreted by the human body (Gros et al. 2010; Wätzel und Kraft 2014a; Wu et al. 2016)(Table 8).

The dilution of blackwater can be affected by the type of collection and flushing system in households. The maximal advantage of separating greywater can be achieved at blackwater collection with minimal water. The more the blackwater is diluted, the more volume should be collected, transported, stored, and treated for the same nutritional value. Furthermore, to avoid excessive dilution of faeces and urine, many types of low-flush toilets are currently available on the market or under development (WRS 2001). The general categories of flushing toilets compared to a traditional system are given in Annex A.4.

A high load of organic and solids content of blackwater makes it ideal for anaerobic digestion. This process can produce energy in biogas and nutrients in organic fertiliser, with a high concentration of nitrogen and phosphorus rather than sewage sludge (Wendland et al., 2007).

Furthermore, separating urine from blackwater improves the process by lowering salt and ammonia content. Lowering water content via low-flush toilets also adds to efficiency. Adding kitchen waste to blackwater can substantially increase methane production. Based on Kujawa-Roeleveld et al. (2006), a fully optimized digestion process may lead to a methane production of approximately 35 lit/(pe.a) (similar values reported by Wendland et al., 2007).

Table 8: Average loads of blackwater

Parameter		Unit	Value
Volume		lit/(pe.a)	49
Solid	**DM**	g/(pe.a)	63.2
	oDM	g/(pe.a)	47.3
Organic	**BOD**	g/(pe.a)	32.4
	COD	g/(pe.a)	51.5
Nutrient (inorganic)	**N**	g/(pe.a)	10.7
	P	g/(pe.a)	1.5
	K	g/(pe.a)	2.7
	S	g/(pe.a)	-

Source: Meinzinger, 2010

3.7.3 Greywater

The most significant volume of domestic wastewater is composed of greywater. It originated from laundry, shower, and kitchen sinks (In general, total wastewater from households expect toilet discharge); each kind has its characteristics and variation. In Germany, from 127 lit/(pe.a) of water demand, about 88 lit/(pe.a) is allocated to greywater. According to BDEW-Wasserstatistik, 36% belong to showers, bathing, and hand washbasin, 12% wash machine, 6% dishwashing, and 6% cleaning washing/gardening (BDEW 2019).

The physical and chemical characteristic of greywater cited in the literature varies widely depending on the water source, quality of water supply, water use, household activities, socio-economic and cultural factors. It is because quality is affected by cleaning and bathing product choices, the number of people in a particular household, and personal habits. According to Sievers (2018), BOD ranges between 5 and 900 mg/L and COD ranges between 23 and 1,600 mg/L. It contains a low number of solids and nutrients, especially when separated from kitchen wastewater, and a high concentration of micro-pollutant (cleaning products, shampoo/ soap, perfumes, cosmetics) and heavy metals originate from dust by wiping out during house cleaning activities and plumbing.

The nutrients in greywater are mainly inorganic, and biodegradability is low. Detergents, dishwashers, and washing machine products affect P load significantly. Potassium and phosphorus are used in detergents, and their concentrations will mainly reflect the usage rate of these products (Henze and Ledin 2001). There is a general push towards eliminating phosphates from detergents in European law. The other sources of nutrients are kitchen residues (food leftovers) ending up in the kitchen sink. Kitchen waste increases the pollution load up to 40-60% (including BOD, COD, oDM).

Most of the available qualitative data are for mixed greywater, but recently the number of studies that differentiate “light” and “dark” greywater (Henze und Ledin 2001; Sievers 2018) is increased. Pathogens are generally lowest in light greywater than all other domestic sources (Friedler und Hadari 2006; Gross et al. 2015 for faecal indicator bacteria). Faecal contamination will undoubtedly occur as an example if cloth diapers are included in the household wash, so this may need to be considered in developing a treatment system.

Greywater collection and treatment is a rapidly growing field, mainly due to water reuse applications (Nolde 2000; Li 2004; Siracusa und La Rosa 2006; Merz et al. 2007; Paulo et al. 2009; Hoffmann et al. 2011).

The results of some studies show that although the feasibility of reuse of treated greywater, the energy demand and the profit of this process is not improved the sustainable criteria (Meinzinger, 2010; Remy 2010), and there are still concerns regarding the persistence of personal care products, salts and pathogens and their effects on soil.

Therefore, in the context of this study, in the section on technologies, the focus is to figure out how the greywater fraction can improve the potential of energy and nutrient recovery, primarily by reducing the volume of high-polluted wastewater for specific treatment.

3.7.4 Urine/ Yellow water

Valuable nutrients recognize in the small volume of urine and a considerable amount of anthropogenic trace organic substances like pharmaceuticals and hormones (Escher et al. 2006; Verlicchi et al. 2012). Separating urine provides a way to close the nutrients and micro-pollutants cycle partially. (Jönsson et al. 2005).

World-wide research and review of urine separation and related technologies indicate urine source separation as a flow to nutrient recovery, water conversation, and decreased overall energy requirement for nutrient and micropollutant removal compared to conventional wastewater treatment. The initial finding also showed that it could be considered a sustainable approach combined source separating methods/ technologies (Dockhorn 2006; Muga und Mihelcic 2008; LeMonde Fewless 2011; Antonini 2013; Sikosana et al. 2017).

Urine is only 1% of total domestic wastewater; it contributes 50-80% of the total nutrients (75-80% of the nitrogen, 50-55% phosphorus, and 70% potassium), and unfortunately, the majority of the pharmaceuticals (Larsen und Gujer 1996; Johansson 2000; Winker et al. 2008).

Macro-nutrients (N, P, K) in urine is water-soluble. Nitrogen is mainly found as urea (80%), ammonia (7%), and creatine (6%); the remaining are mainly amino acids (Ganrot 2005; Tettenborn 2011; Randall und Naidoo 2018). The phosphor is mainly inorganic phosphates (>95%) and potassium, typically as free ions. In addition, urine is also a significant source of pharmaceuticals and their metabolites excreted to the environment (Ronteltap et al., 2007).

Urine source separation could improve water quality by preventing pharmaceuticals and hormones from entering aquatic ecosystems by technologies for removing micropollutants (e.g., membrane filtration, reverse osmosis, ozonation). Since these technologies are still too costly and energy-intensive, separating urine can be implemented for a much smaller volume, decreasing capital cost, maintenance, and energy required (Lind et al. 2001; Ganrot 2005; Dodd et al. 2008). Therefore, in this study, the related urine separation technologies are investigated, which are the results of a small-scale study, and it is upscaled.

3.7.5 Biowaste from kitchen and garden

German biodegradable waste is collected separately and recycled as organic fertiliser in compost and digestate. Biowaste recycling has contributed to global warming potential and energy production by biogas from fermentation.

According to the EU's waste framework directive, the Waste Management Act of 2012 (KrWG, 2017) in § 11 paragraph 1 obligates waste producers and mandated waste management authorities to collect bio-waste separately. The requirement in the Waste Management Act (KrWG) to collect bio-waste separately (§ 11/2 KrWG) is defined in the Bio-waste Ordinance (BioAbfV) (Schüch et al. 2016). The term "biowaste" in § 3 KrWG includes yard, park, and landscape management waste as well as food and kitchen waste.

Despite the increase of the potential of nutrient recovery in terms of energy production and fertiliser by pairing the biowaste with other wastewater flow (Vogt 2002; Schmidt und Pahl-

Wostl 2007), due to the set rule in Germany for the separate route for biowaste, this flow is excluded from this study, and it is only the biowaste from the kitchen which is entered from the sink is considered as a source of biowaste. The characteristic of biowaste from the kitchen and garden is presented in Annex A.3 (Table A.18), which presents information about the kitchen and garden biowaste from the household that is collected by using biowaste bins. It is strongly related to the structure of the urban area, specifically the occupied green space area, inhabitants' behaviour, and the annual seasons.

3.7.6 Drinking water supply

Although drinking water supply is not part of wastewater flow but considering their influence on the dilution of wastewater, it has been investigated as a supplementary flow in this study.

Drinking water supply is essential in water resource demand, energy demand for treatment and distribution, and nutrient and heavy metals concentration.

The quality of drinking water is partly influenced by water contact with pipe and construction materials (Table 9) (Schulz et al., 2003; Remy 2010). The dissolution of copper and zinc from pipe material affects the number of heavy metals in drinking water which will be discharged as flush water and in greywater production. Therefore, the most important source of heavy metals is coming from drinking water. The corresponding value of the heavy metals in different flows is shown in table 8 but considering the variation of heavy metals during different processes of wastewater is beyond the goal of this study.

Table 9: Average load in drinking water supply

Parameter		Unit	Drinking water supply
Solid	**DM**	mg/l	300
	oDM	mg/l	-
Organic	**TOC**	mg/l	1.1
Nutrient (inorganic)	**N**	mg/l	1
	P	mg/l	0.08
	K	mg/l	7.5
	S	mg/l	40.5
Heavy metal	**Cd**	mg/l	0.0005
	Cr	mg/l	0.005
	Cu	mg/l	0.16
	Hg	mg/l	0.0002
	Ni	mg/l	0.005
	Pb	mg/l	0.005
	Zn	mg/l	0.37

Source: Meinzinger, 2010; Remy, 2010

3.8 Developing the concept of the mathematical model

A wastewater process model consists of several mathematical equations describing reaction and variation rates of various biological, chemical, and physical processes. Simulators imitate the operation of a real-world process using simulation of the main characteristic of the processes. Many process models have been developed over the years to the point where they are now used to develop simulators that are widely used for the process design, facility evaluation, troubleshooting (CML 2001: GaBi Software; Jeppsson et al. 2005; Henze et al. 2006; Campos 2013; Castillo et al. 2016).

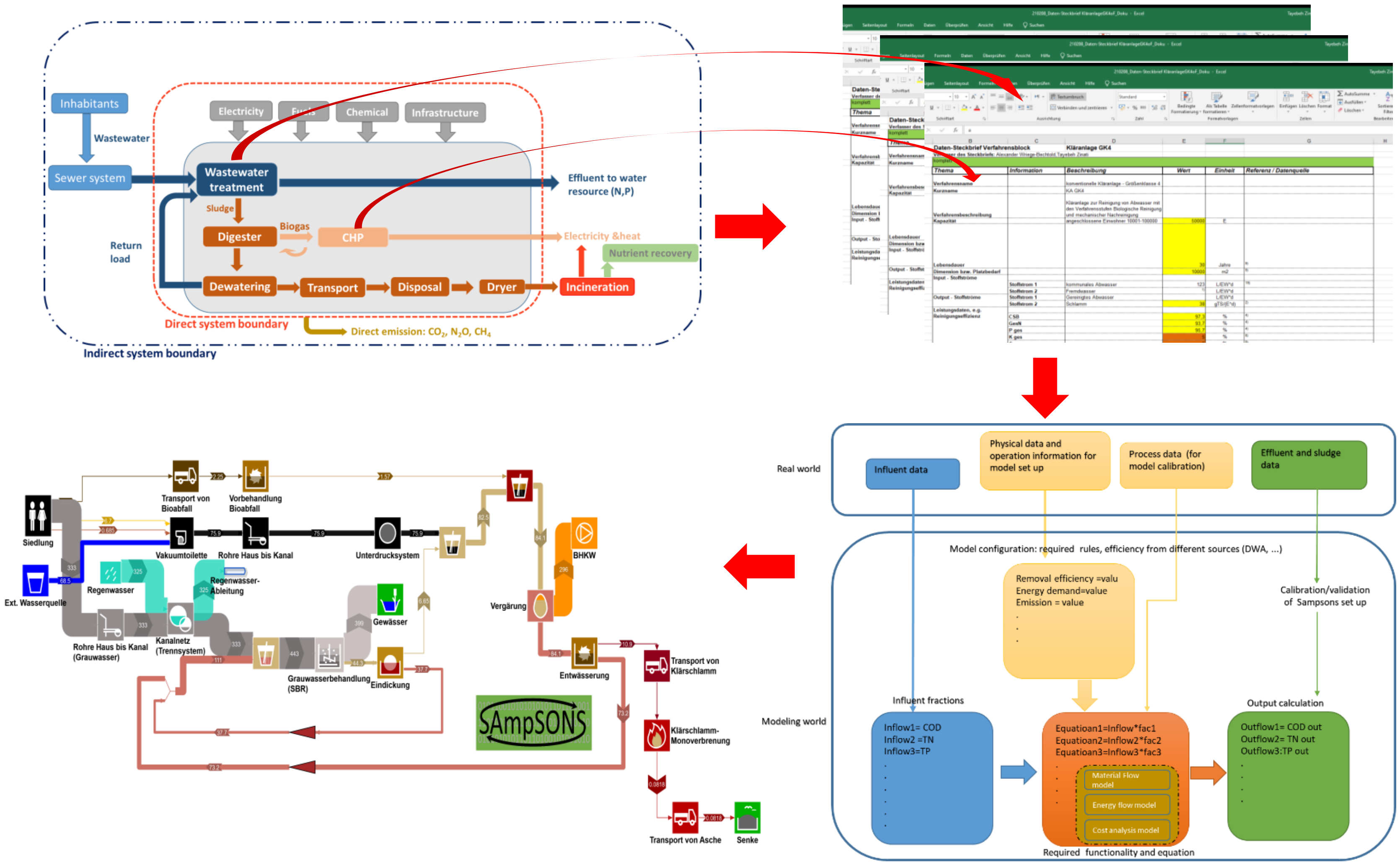
Despite well-developed models for the conventional wastewater process, there is still a lack of a robust simulator for the source separation sanitation concept. Hence, in the context of this study, a process model is developed to evaluate the source-separated sanitation concept to represent the MFA of each scenario. As explained in this study's approach, the mathematical model, MFAR3, combines mass flow, energy flow, and cost model. It is developed based on the corresponded equations for mass /nutrient, energy flow, and cost for each process unit. The combination of these models provides an integrated analysis of different concepts to define the criteria of sustainability (Figure 20).

The model is tailored for European circumstances with a specific focus on Germany. However, the model is applicable for other circumstances with input data and coefficients modification.

The platform of Simba# (ifak technology + service GmbH) is selected to reflect these equations. One reason for selecting this platform is that this software provides a relatively flexible platform for implementing the concept for conventional and source separation sanitation systems. On the other side, according to a project in DBU (2016-18; grant reference 32768), an extension tool has been developed to visualize the material flow of the new sanitation system. SAmpSONS[5] tool (ifak technology + service GmbH 2017) provides a platform to generate extensive alternatives of urban sanitation systems according to the treatment requirements and the decision-maker desire. Although this tool is in the preliminary phase, the goal was to estimate urban planners roughly. However, it has a high potential to improve /extend resource recovery technologies by considering sustainability criteria.

The following sections describe the fundamental equations of the model for material flow, energy, and cost analysis. The specific equations for each process are explained in the unit process. This combination of models allows an integrated assessment of the investigated concepts in this study.

[5] The tool is available online and can be used for other studies by changing the default value: https://www.ifak.eu/en/products/sampsons



Source: Self-developed

Figure 20: The functionality of the model

3.8.1 Material flow analysis

The principle of this model is based on classical material flow analysis. The calculation of mass flow and its flow characteristics is based on an n*m matrix with n number of raw material (source-separated wastewater, GW, BW, YW) and m number of the different characteristics of each flow, including COD, N, P, K, and key indicators of sustainability (Cote 2016) by model equations. The solution of the n-equation system calculates the required processed raw material Ai, j, t volumes to produce final goods.

Equation 1 determined the mass production for each flow and corresponded characteristic per capita consumption.

$$\sum_k A_{j,k}^n = \sum_i A_{i,j}^n - M_j^n \qquad (1)$$

A: flow

n: parameter i.e., mass, COD, N, P, K, …

i: input

k: output

j: balance process

M: stock rate change (accumulation, degradation)

Each process unit computes the material behaviour based on accumulation, degradation, or transfer. Equation 2 calculates the required amount of processed flow characteristics based on the accumulation or degradation of nutrient/ material production participation from equation 1.

$$A_{j,k}^n = m_{j,k}. c_{j,k}^n \qquad (2)$$

m: mass flow

c: concentration of material

A: flow

n: parameter, i.e., mass, COD, N, P, K, …

k: output

j: balance process

Equations 3 and 4 calculate the produced amount of each parameter of every defined flow based on the transfer coefficient. The transfer coefficient represents the distribution properties for the outgoing material from the process unit. Since it is technology-dependent, they can evaluate the impact of alternative or new technologies on the flow of materials through a system.

$$A^{n}_{j,k} = \sum_{i} A^{n}_{i,j} \,.\, tc^{n}_{j,k} \qquad (3)$$

$$tc^{n}_{j,k} = \frac{tc_{j,i}}{\sum^{n}_{k} tc^{n}_{j,k}} \qquad (4)$$

tc: transfer coefficient

A: flow

n: parameter, i.e., mass, COD, N, P, K, …

i: input

k: output

j: balance process

As a part of material flow analysis, the supplementary flow, including emission from each process unit and chemical supply, is also considered.

3.8.2 Energy flow analysis

Regarding the critical role of energy in the sanitation system, alongside material flow, energy balance model has been implemented based on equation 5:

$$\sum_{k} En^{n}_{j,k} = \sum_{i} En^{n}_{i,j} - \sum_{j} En^{n}_{j} \qquad (5)$$

Enj: residual energy in the system

Eni: energy demand for collection, treatment, transport

Enk: energy recovery including from methane heat and electricity

Energy analysis is based on the stationary model, and only direct energy requirement is taken into consideration, which is related to the sanitation system in the defined boundary condition.

Energy demand is the energy required for the collection, transport, and treatment of the physical, biological, and chemical treatment processes in the form of electricity and heat. The type of energy depends on the type of processes and the selected energy; thus, each process unit's energy demand is assigned directly to that process. The detailed description of the energy parameter of each process unit is explained for each process unit in chapter 5.

The energy produced from different processes such as anaerobic digestion and incineration is estimated as energy recovery. To calculate this part of the energy, the energy model is directly coupled with the flows of each process unit in the model. It means that nutrient and organic carbon inflows are used as input values to calculate the energy production of the system's energy balance.

In order to equivalent different forms of energy and estimate the amount of the recovered energy, all energy types were calculated as primary energy by converting to primary energy demand using a coefficient factor based on the European energy mix (Annex A.2, Table A.12).

3.8.3 Cost analysis model

In order to ensure a comparative economic evaluation of the different processes and scenarios, different aspects of costs have to be considered. It is included investment, operation, and revenue from the product of wastewater treatment processes. Operation cost counts for maintenance, material supply, and personal and disposal costs.

The cost analysis model is expanded with statistical information from various pilot plants located in Germany. It includes the conventional wastewater treatment process and data cost from the source-separated pilot plant, which is considered that source-separated processes due to small scale have uncertainty. It contains various cost equations that will provide the facility to estimate the cost of each process.

The modelling approach analyses the effectiveness and cost of different process units in the sanitation system. It is identified the investment and operation cost of each process. According to (Hernandez-Sancho et al. 2011), the cost analysis is divided into three categories.

Capital cost estimation based on equation (6) includes engineering, civil works, construction, mechanical, electrical, and land cost.

$$\mathrm{I} = \mathrm{AQ}^{\mathrm{n}} \qquad (6)$$

Where

I: total cost for investment (€)

Q: flow rate (m^3/d)

A and n: constant parameters based on related population equivalent and local condition of each process unit

The cost of operation and maintenance (O&M) is based on equation (7). This equation applied some representative parameters like energy demand, use of chemicals, labour, sludge disposal to quantify the functionality of different processes. Comparison among the various technologies is provided by applying this equation. The respective equation of each process unit will be explained in chapter 4 in the related section for each one.

$$C = AV^b e^{(\sum \alpha_i x_i)} \qquad (7)$$

C: operation and maintenance cost

A, b, and α: coefficient

V: the volume of wastewater

Xi: the representative variable of process units

Revenue/saving based on the net profit value is considered for the process units with external products (i.e., fertiliser, energy production) (Lema und Suárez 2017).

It is necessary to mention that this study's goal is only to consider the cost parameter as one of the main pillars of sustainability. The specific cost for each process unit can vary (150-200%) compared to the average value due to the utilized capacity, plant size, and wastewater characteristics. Hence, observing the variation of cost is beyond the goal of this study. The cost model is developed in the tool to provide a platform for comparing different scenarios. Thus, the fixed assumption for each process unit is collected from different pilot plants and literature.

Despite the relation between cost and the related population for different sizes, this trend is not observed in this study due to avoiding complexity. As mentioned in the study goal, the group class of more than 100,000 population equivalent (GK5) is considered. The capital cost is calculated based on 50 years of a lifetime based on EU regulation (Oldenburg 2007), although the life span of wastewater treatment is more than 50 years.

4 Description of selected process units for sustainable sanitation

4.1 Structure of functional groups

Due to the various possibility of available technologies in each step of sanitation, data processing of all selected process units in this study is described in the following chapter based on the functional group, which is introduced in section 3.3. As it is mentioned, the functional group includes various options of process units, which enable the assessment of sustainability in sanitation systems.

Hence, in each process, unit input and output are considered in terms of inflow, outflow, emission, energy demand, chemical, and cost variation, which can influence the sustainable assessment results.

4.2 Process units for collection

The user interface's functional group represents a core process for the modelling. It includes a household, in-house piping system, and drinking water supply unit process.

4.2.1 Household

The household process unit plays an essential role in the modelling of this study. This unit defines the relevant parameter of generated wastewater flow in households and collection systems (Table 10).

The main inputs of this unit are food, drinking water, and detergents (e.g., cleaning agents, washing powder shampoo, soap, cosmetics, pharmaceutical) that represent in output as different fractions of wastewater, including urine/ yellow water, faeces/ brown water or combination of urine, faeces, and flush water (blackwater), greywater and organic waste from the kitchen. The characteristic of these flows (mass and nutrients) is derived from the extensive literature review, and the data processing is shown in the following chapter. The nutrient flows and corresponding criteria like energy demand, costs, etc., of each flow are estimated based on the daily load per person related to the material and energy flow functions that are introduced in section Annex A.3.

Since the separation efficiency depends on the selection of the collecting system, the efficiency ratio is considered the main criteria for each flow (Peter-Fröhlich et al. 2007; DWA-Arbeitsgruppe KA-1.6 2017).

The cost and energy factor of the household process unit is mainly related to the functionality of the toilet system and in-house piping system. Various toilet systems significantly impact the sustainability criteria since mixing faeces and urine with flush water cause a dilution and high volume of wastewater. These technologies focus on processes that transport the high load nutrient to the treatment plant. In this study, three types of toilets are considered: conventional, low flush toilets, and vacuum. A low flush toilet is a high-efficiency toilet that uses significantly less water (14 lit/pe.a) than a conventional one (30 lit/pe.a). The complementary data for different toilets has been shown in Annex A.4 regarding the cost and water demand used for the modelling process.

Table 10: Overview of household process units in the user interface functional group

Sanitation concept	Flow type	Flow source	Collection system	Drainage system	Remarks
Conventional	Mixed wastewater	Toilet	Mixed toilet	Gravity	Mixed of faeces, urine, and flush water which will drain with greywater to the sewer pipe
		Hygiene activity: bathing, cleaning, washing	Pipe	Gravity	
Source separated	Blackwater	Toilet outflow	Mixed toilet	Gravity	Mixed of faeces, urine, and flush water
				Vacuum	
	Brown water		Separate collection toilet	In-house piping	Separation of urine from faeces and flush water
	Urine			Vacuum	
	Greywater	Greywater outflow	Pipe	Gravity	Separate sewer pipe to the treatment process

4.2.2 In house piping system

Source separated in-house piping system on the household level increases the degree of complexity. It can be differentiated into a dual piping system (collection of backwater and greywater) and triple piping system (collection of separated urine, brown water, and greywater) or, in case of greywater reuse, the separate pipeline for treated greywater (Kujawa-Roeleveld und Zeeman 2006; Fewless 2015; DWA-Neuartige Sanitärsysteme 2015)

The piping system and vacuum pipes, and in-house installation were calculated based on the installation requirements given by Buchert et al., 2004 and Remy 2010. The average value of pipe length for urban areas is estimated at 2±0.4 m/pe (Meinzinger 2010). The multiple piping systems of the source-separated concept will be reflected by aggregating the required length of pipe for each flow and calculating the required length increases 2 or 3 times more than the conventional system according to the dual or triple system.

Decisive parameters for comparing the source-separated and conventional concept are significantly the costs due to material demand for separated flow concept. However, energy recovery's energetic benefit may offset the high cost of the pipe system for the source-separated concept. Therefore, the material demand for each type of piping system and corresponding costs are considered in the modelling process, and the assumed value is presented in Table 11.

Table 11: Cost related parameter for in-house piping system

Parameter	Value	Unit	Source
Pipe length in-house per person	2±0.4	m/pe	1,2
Lifespan pipes	50	year	2
Vacuum pipe in-house	57	€/m	3
Urine pipe	28	€/m	4
Sewer house connection	1,283	€/ building	3
Vacuum pipe house connection	427	€/ building	3
Urine pipe house connection	427	€/ building	3
Maintenance urine pipes	3	% Investment	2
Maintenance pipes, house, etc	1	% Investment	2

1) Buchert et al., 2004 2) Meinzinger, 2010 3)Oldenburg and Dlabacs, 2007 4) Herbst, 2008
*Cost is updated to 2019 based on a 3% interest rate

4.2.3 Drinking water supply

The unit of water supply is defined to determine the water consumption in the household and, consequently, the rate of wastewater dilution. The volume of wastewater that passes through the system is highly dependent on the water demand of the households, which varies based on the pattern of demand and the infrastructure, i.e., toilet and piping system. This amount is estimated as water demand for the activities like eating and drinking (5 lit/pe.a), personal hygiene (46 lit/pe.a), laundry (15 lit/Pe.a), cleaning and gardening (8 lit/pe.a) (BDEW 2019) toilet flushing (3-30 lit/pe.a) (Meinzinger, 2010). Table 12 shows the water demand of different toilet systems.

Table 12: Water demand, cost, and life span of different toilets

Toilet type	Water demand (lit/pe.a)	Cost (€)	Life span (year)
Conventional toilet	30	250-300	20
Conventional low flush (two buttons)	14	-	20
Vacuum toilet	6	600-980	20
Urine diversion toilet (gravity)	5	450-950	20
Urine diversion toilet (vacuum)	2	700-1500	20

Source: see Annex A.4

The water supply process unit is also essential in energy demand to produce drinking water and transport it to households and conversation of water resources. The specific energy demand of the drinking water supply (including treatment and supply) is assumed to be 0.51 kWh/m^3 (DVGW 2011).

The German average drinking water supply, including tax and basic fees, is 1.694 €/m^3 (2019, BWB). According to Evers's study (Evers 2009), the cost factor (around 80-90% of total cost) is mainly for upgrading and maintaining infrastructure. Therefore, the cost factors are not reduced even when the consumption is decreased. It is expected that the decreasing water demand will have less impact on the total cost of water supply.

4.3 Process units in transport /drainage

Transport processes include piping in the house, sewer and pumping system from household to treatment plant, and truck (Table 13 and 14). The sewerage system of a conventional concept consists of a mixed sewer pipe from the household directed to the urban sewer network. Source separated concept adds more challenges regarding the transfer to the treatment plant. On the other side, the smaller volume of the source-separated concept makes it easier to handle; however, the increased number of flows requires alternative transport (BDEW 2019) systems and pipes than the conventional sewer system.

Possible emissions of wastewater during drainage (e.g., emission NH_3, H_2S) are neglected to avoid the complexity of the simulation and groundwater infiltration, or possible leakage of the piping system is not considered.

Table 13: Overview of process units in the transport functional group

Sanitation concept	Flow type	Drainage system
Conventional	Mixed wastewater	Gravity sewer[6]
Source separated	Blackwater	Gravity sewer Vacuum sewer Pressured sewer
	Brown water	
	Urine	
	Greywater	Gravity sewer

[6] The sewer system in this study is considered separated sewer system for rainwater

Table 14: Cost related parameter in sewer systems from house to treatment plant

Parameter	Value	Unit	Source
Conventional sewer	427	€/m	1
Pumping station[7]	5.85	€/pe	1
Vacuum sewer	85	€/m	2
Vacuum station[6]	86	€/pe	1
Sewer maintenance[6]	55	€/(pe.a)	3
Vacuum sewer maintenance	2	€/m	3

1)Oldenburg, 2007 2) Herbst, 2008 3) Meinzinger, 2010
*Cost is updated to 2019 based on a 3% interest rate

4.3.1 Transport by truck

Truck-based transport has a significant role that should be considered in analysing source-separated concepts for transporting urine or sludge and recovered products. Different flows with various volumes and characteristics (liquid, solid product) cause different logistical aspects; therefore, it is necessary to consider the proper transport for each flow type and different trips.

The following equations (8 and 9) are defined to calculate the total distance and number of trips based on the volume that should be transported (Meinzinger, 2010):

$$\mathrm{Naj} = \mathrm{Inh\,j} * \mathrm{vol} * \mathrm{F} / \mathrm{Max\ load}_{\mathrm{truck}} \qquad (8)$$

Naj: number of trips to destination j

inhj: number of inhabitants j (p)

vol: volume or load to be generated (per person and day) (kg/pe.a) or (m^3/pe.a)

F: frequency of collection (i.e., every day) (d)

M: the maximum load of truck (kg) or (m^3)

$$\mathrm{L} = \sum \mathrm{Naj} * \mathrm{Ddistance} \qquad (9)$$

L: total distance of trips [km]

Naj: number of access trips to district j (-)

Ddist: distance between district/neighbourhood and depot (km)

[7] Including construction with lifespan 50year, maintenance and electrical equipment with lifespan 12.5year

The distance of the truck is modelled for the calculation of emission caused by the demand for fossil fuel using the defined equations. In addition, the fuel demand for the transport of urine, sludge, and other products is considered based on liquid and solid material. The return trip is considered an empty truck and related fossil fuel consumption (Table 15). The list of the different transport possibilities considering the distance for different flow/materials is presented in Annex A.6. The related fossil fuel emissions are collected in Annex A, Table A.14. The cost for transport is assumed 5.22 €/km based on Meinzinger (2010) and updates interest rate till 2019.

Table 15: Fuel demand for transport of different material

Parameter	Full truck (lit/km)	Empty truck (lit/km)
Liquid transport	0.35	029
Solid transport	0.24	0.18

Source: IFEU and SGKV, 2002; ORNL, 2008; DIN, 2007; DWA-Arbeitsgruppe KA-1.6 2017

4.3.2 Pumping and vacuum system

In conventional concept, wastewater from a household to a treatment plant is transported by a gravity drainage system.

In the source separation concept, vacuum sewer provides the facility to collect and transfer urine and faeces with few amounts of flush water, leading to less dilution of wastewater flow. It saves about 19 lit/(pe.a) of flush water (Remy 2010). Table 16 shows the different amounts of water and energy demand for two different systems of gravity and vacuum system.

The vacuum system must transport high concentrated wastewater to minimize detention time and odours and conserve the nutrient recovery potential. The advantage of the vacuum system compared to the gravity system is the transport of wastewater at a faster rate, requiring only a single pump station and being monitored remotely. The vacuum system relies on differential pressure and negative pressure (ca. -0.5 bar) to collect flows (Peter-Fröhlich et al., 2007). It consists of vacuum drainage and a vacuum station. A vacuum station consists of a tank and pressure pump to deliver the collected wastewater to the treatment plant. Vacuum sewers are generally shallower than conventional sewers, enabling easier access for maintenance. On the other side, the vacuum system is more expensive than gravity sewer, and long pipes with few connections can perform poorly. Remote and regular monitoring of effective operation is critical. Vacuum valve failures and leakage detection can be more complex than gravity sewers.

Although a vacuum system has not been implemented yet in the scale of urban areas, it has been successfully tested for urine and blackwater (Zeeman und Kujawa-Roeleveld 2011), Peter-Fröhlich et al. (2007), Otter-wasser (2009), Zhang (2016), and Burgada Ruiz (2016) are a few examples. Noise behaviour for the user of vacuum toilet, transport, and treatment system must be adaptable to variable loading, and designing parameters should be considered.

The use of a vacuum toilet led to saving energy demand of drinking water supply by 3-7 kWh/(pe.a) (Lindner 2007); however, the required energy demand of the vacuum system is generally higher than the gravity system.

The energy demand of the vacuum system from several references varies between 7 to 51 kWh/(pe.a) (Annex A.7). According to the volume of transported wastewater in the different cases, it can be converted to 3 to 28 kWh/m^3 for assumption in the modelling process (Table 16). Despite that, the lower values have been achieved in the lab scale. The higher value results from systems are not working efficiently; therefore, for this study, the energy demand of 15 kWh/m^3 is assumed for the energy demand.

Table 16: Water and energy demand of different drainage system

Drainage system	Water demand for each flushing	Energy demand (kWh/m^3)	Source
Conventional	5	0.12	Balkema, 2003
Vacuum	1.2	3-28	Meinzingr 2010

Emission to air during transport is mentioned in various literature, 1% (Remy, 2010) of the total emission of wastewater process. Therefore, in this study, the emission from the sewer system is neglected.

The capital cost in the transport process is directly influenced by various parameters such as the diameter of the pipe system, the depth of the pipe system, soil type, material. Cost for sewer and pump stations is assumed based on information in Table 14.

4.4 Process units in the treatment

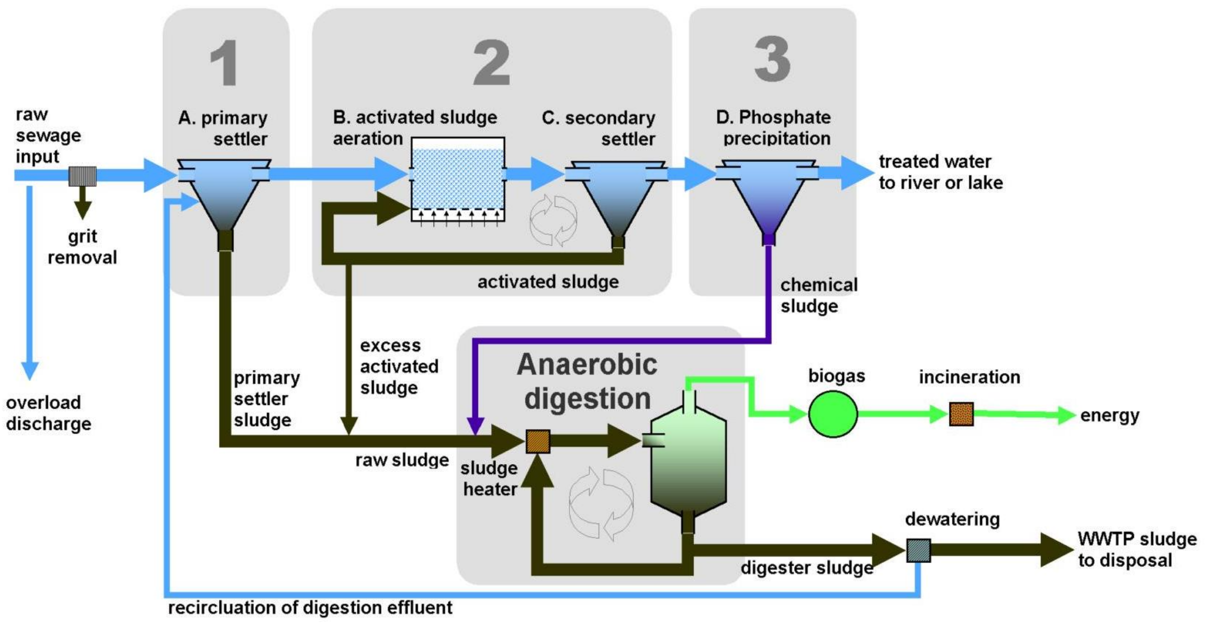
The treatment process unit plays a decisive role in removing or recovering valuable material and energy balance. This process unit is divided into three main subcategories: wastewater treatment by the mechanical primary treatment, biological and chemical reaction in secondary treatment (Table 17). In order to complete the treatment process, sludge treatment and sludge liquor treatment are the supplementary stages (Figure 21).

In the sludge stage, the primary and secondary sludge is digested in anaerobic reactors, which lead to biogas production. This gas is combusted in a CHP plant to produce electricity and heat. The digested sludge is directed to the disposal route after dewatered, drying, and incineration. Sludge liquor is mainly returned to the beginning of the wastewater treatment process, which causes additional energy demand for the oxidation reaction.

Although the conventional wastewater treatment process is continuously optimized, there are still many discussions regarding the energy demand improvement of the secondary treatment and biogas production in the digestion process. In addition, the potential of the source-separated system should be considered.

Table 17: Overview of process units in treatment functional group

Sanitation concept	Flow type	Type of wastewater	Treatment system		
			Primary treatment	Secondary treatment	Post-treatment
Conventional	Mixed wastewater	Wastewater	Sedimentation	Activated sludge treatment	
		Sludge	Dewatering	Anaerobic digestion	
				UASB	
				Aerobic digestion	
				Co-Digestion	
		Sludge liquor		SBR	Flocculation
				Return to treatment cycle	
Source separated	Urine			Storage	
				Evaporation	
	Blackwater/ Brown water	Sludge	Lime treatment	Anaerobic digestion	Dewatering
					Thickener
		Sludge liquor	Liquid-solid separator	SBR	
				MBR	
	Greywater		Sedimentation	Activated sludge treatment	UV
				Constructed wetland	Chlorine
				SBR	Ozone
				MBR	Activated carbon



Source: (Muñoz et al. 2007)

Figure 21: Conventional process of wastewater treatment

4.4.1 Wastewater treatment process units

The conventional wastewater treatment process unit is based on removing nutrients in wastewater. The energy and nutrient recovery potential is mostly not considered in this approach, and the wastewater is considered an environmental issue rather than a resource recovery potential.

The treatment process unit for the conventional concept is modelled based on the activated sludge plant as a fundamental treatment process for modelling in this study. The conventional activated sludge process is the most widely used process to remove nutrients and covers nutrients removal by mechanical, biological, and chemical treatment of combined wastewater.

The parameter calculation in the model is based on the linear input-output relationships throughout the transfer coefficients. These coefficients represent the behaviour of substance by the particulate ratio that is the removal efficiency of substance in the output of each unit process. The mass balance of each process unit is considered to calculate the material flow of nutrients emitted to air or flowed to liquid phase (treated wastewater/sludge liquor) or solid-phase (sludge). It is collected based on an extensive literature survey for each process. The selected data for modelling the wastewater treatment process is presented in Table 18- 19 (Gernaey et al. 2014; Lema und Suárez 2017).

The configuration of the developed tool is formulated based on the assigned load of inflow into a process unit to calculate different criteria that lead to evaluating various aspects of sustainability. For example, it is expected that for greywater, which has less contamination load than mixed wastewater, the demand for energy decreases significantly. Consequently, the other essential criteria in terms of sustainability can be considered.

Table 18: Functional data of conventional wastewater treatment process unit

Parameter	Removal efficiency of each process (%)		
	Physical	Biological	Chemical
COD	35	95.4	-
N	11	83 [1]	-
P	17	0	93.1 [2]
K	0	no data	no data

1: Including nitrification and denitrification

2: By adding Fe

Source: LCA model, TU Berlin, Remy, 2010; Barjenbruch, M. (2015): DWA Leistungsvergleich 2014

Table 19: Mass balance of nutrients in the conventional wastewater treatment unit

	Parameter	Effluent	Sludge	Air	Sewage gas
COD	COD-C	6.8			
	CO_2-C			44.7	8
	CH_4-C				15.4
	C-organic		25.1		
N	N dissolved	8.9			
	N_2-N			72.7	0.1
	NH_3-N			0.3	
	N_2O-N			0.4	
	N sludge		17.6		
P	-	4.2	95.8		
K	-	95	5		

Source: LCA model, TU Berlin, Remy, 2010

The wastewater treatment process is the most energy demand section in the system. Around 60% of the total electricity demand is attributed to the aeration of the activated sludge reactors to reduce organic matter and nitrogen (Meinzinger 2010). In order to reflect the variation of energy demand in the modelling, the energy demand parameter is set up according to the semi-dynamic and static classification. The semi-dynamic energy demand calculation depends on a load of wastewater affected by the nutrient load (COD, N, P…). It will calculate energy demand based on different loads. The Static energy demand is based on wastewater flows that affect the energy requirement for aeration, pumping, flotation, mixing and dewatering, digester, etc. This configuration is helpful for the calculation of energy demand for different less concentrated inflow like greywater or high concentrated flow like return flow from digester and dewatering processes. Table 20 and 21 shows the related energy data for this unit.

Table 20: The energy demand of different nutrient removal

Parameter	Unit	Value	Source
COD elimination	kWh/kg COD_{elim}	0.5	DWA-A216, 2015(calculation)
BOD_5 elimination	kWh/kg BOD_{5elim}	0.7	Meinzinger, 2010
N_{total} elimination	kWh/kg N_{elim}	3.8	
NH_4-N elimination	kWh/kg NH_4-N_{elim}	2.28	DWA-A216, 2015(calculation)
NO_3-N elimination	kWh/kg NO_3-N_{elim}	1.43	
P elimination	kWh/kg P_{elim}	0.37	Remy 2005 (Müller et al., 1994 & LfU, 1998)

Table 21: Energy demand different processes in the conventional wastewater treatment system

Parameter	Unit	Value
Mechanical treatment and sedimentation	kWh/kg dry matter	0.08
Primary sludge pumps	Wh/ (m^3 m pressure head)	6
Aeration for carbon degradation	kWh/kg $COD_{respirated}$	0.55
Aeration for nitrification	kWh/kg $N_{nitrified}$	2.34
Benefit from denitrification	kWh/kg $N_{denitrified}$	-1.58
Internal circulation	kWh/m^3 wastewater	0.01
Recirculation and mixing	kWh/m^3 wastewater	0.05
Clarifier	kWh/m^3 wastewater	0.01
Infrastructure of WWTP	kWh/m^3 wastewater	0.03

Source: Remy 2010 based on LFU, 1998, Müller et al., 1999 (all the value, except 2: Dokhorn, 2006)

The cost for wastewater treatment is dependent on the size of the plant, capacity, and characteristic of waste flow; even for the exact size of the wastewater treatment plant, it can differ up to 150-200% of the average value (Reicherter, 2001; Meinzinger, 2010). Hence, the cost analysis in the modelling and sustainability assessment stage is rough.

According to the studies from Dockhorn (2007a), Meinzinger und Oldenburg (2009), and Hernandez-Sancho et al. (2011), the attribution of cost with the removal of nutrients (COD, N, P, K) can represent the cost occurring at the wastewater treatment concerning the characteristic of inflow. The cost allocation for removing the different nutrients is shown in Table 22. The respective operational costs have subsequently been related to the operation data of flow rate and respective characteristic flow rate removed during the treatment process to achieve the cost for each process unit. The fixed operating costs are considered based on the wastewater treatment process like pumping, aeration, chemical demand (Annex A.8). Capital cost is considered to correlate with the population equivalent (Table 23).

Table 22: Specific cost for the removal of wastewater content

Parameter	Specific cost (€/kg removed)
COD	0.2
N	1.51
P	3.08

Source: Meinzinger, 2010, Dokhorn, 2007
Cost is updated to 2019 based on a 3% interest rate

Table 23: Cost equation for the conventional wastewater treatment system

Parameter	Equation	R^2	Source
Investment cost	$C_{invest} = 39.977 * PE^{-0.435}$	0.766	Zimmermann et al., (1996)
Operational cost	$C_{O\&M} = 2.518 V^{0.7153} e^{(0.007A+1.455COD+0.258N+0.243P)}$	0.730	Hernandez-Sancho, F., et al., (2011)

Where C is the total cost in €/year; V is total wastewater treated volume in m3/year; A is the WWTP age in years; SS is suspended solid removal efficiency in %; COD is chemical oxygen demand removal efficiency in %; BOD is biological oxygen demand removal efficiency in %; N is nitrogen removal efficiency in %, and P is phosphorous removal efficiency in %.

In order to figure out the function of the process unit for source-separated flow (greywater, blackwater, and yellow water), the related technologies have been evaluated for each specific flow. An extensive overview of related technologies for each flow type is presented in Annex A.9 and implemented in the tool's database. In order to avoid the high number of defined scenarios in this study, the selected functional value is chosen based on the minimum difference with conventional wastewater to keep the same basis for comparison and evaluate the effect of nutrient concentration in flow like greywater and yellow water. The selected process units are expected to be comparable to conventional units to analyse their performance.

4.4.1.1 Greywater treatment

With the low load of nutrients and organic matter and high volume of greywater, this flow gets attention for water recovery. It is important to avoid the dilution of wastewater for sludge treatment. Commonly used treatment systems to remove nutrients and organic matter in greywater can be divided into the high rate and low-rate systems.

The conventional activated sludge process seems to be a proper system for nutrient removal (C, N, P). It can be adjusted as an SBR or MBR according to the expected quality of effluent. Referring to Larsen et al. survey (2013), 90% of the systems are implemented based on aerobic biological treatment.

The operational data and mass balance of greywater treatment is set up based on the LCA study in TU Berlin (Remy, 2010), and the value is presented in Tables 24 and 25.

Energy and cost are adopted from conventional wastewater treatment. According to the definition of the equation based on the concentration of flow, the result would be reprehensive of greywater treatment.

Table 24: Functional data of process units for greywater treatment

Parameter	Removal efficiency of each process		
	Physical	**Biological**	**Chemical**
COD	15	93	-
N	11	96 [1]	-
P	10	0	86 [2]
K	0	no data	no data
1: including nitrification and denitrification			
2: By adding Fe			

Source: LCA model, TU Berlin, Remy, 2010

Table 25: Mass balance of nutrient in process units for greywater treatment

Parameter		Effluent*	Sludge*	Air*
COD	COD-C	5.8		
	CO_2-C			78.2
	CH_4-C			
	C-organic		16	
N	N dissolved	27.7		
	N_2-N			39.5
	NH_3-N			0.3
	N_2O-N			0.2
	N sludge		32.3	
P	-	9.3	90.7	
K	-	100		
Source: LCA model, TU Berlin, Remy, 2010				
*Value is based on %				
4.2% of N uptakes by plants				
45% stays in the filter material				

4.4.1.2 Urine treatment

Several studies of urine separation technologies indicated this separation as a sustainable approach to improving water quality, recovering nutrients, and decreasing operational energy demand to remove nutrients and micropollutants.

According to urine treatment targets to eliminate the pollutants and produce a proper fertiliser, technologies for removing micropollutants (e.g., ozonation, reverse osmosis, membrane filtration) are costly and energy-intensive. By separating urine from other wastewater flow, these technologies can be applied for a much smaller volume and potentially decrease energy requirements, capital cost, maintenance (Lienert und Larsen 2010; Dodd et al. 2008). The review of different technologies for urine treatment is presented in Annex A.9.2., mainly collected from Mauer (Mauer et al., 2006) and SCST study in Germany (Peter Fröhlich, 2007) and LCA study in TU Berlin (Remy, 2010) and Tettenborn (2011). Referring to the review of different technologies, removal of pathogens occurs during storage (Germer 2009, Johansson 2000; Tilley et al. 2014), and processes like ozonation and reverse osmosis can accelerate it.

Since the result of a study (Remy und Ruhland 2006) shows a substantial increase of acidification by direct application of urine in the field, in this study, technologies are considered that processed urine to a fertiliser product as struvite or liquid fertiliser (see section 5.5.2 for more detail).

Table 26 shows the mass balance of storage in this study. In addition, the emission of nitrogen in a different form of NH_3, N_2O, and NO_x is considered. The emission of nitrogen during collection (0.003%) and transport (0.01%) is relatively small. However, most nitrogen emissions occurred during urine application on the field, which is accounted as emission in the application as a fertiliser process unit (see section 5.6.2 for more detail). The cost-related data for urine treatment is presented in Annex A.8.

Table 26: Mass balance of urine storage

Target	Parameter	Product	Residual
Hygienisation with a 6-month storage	C	99	1
	N	99	1
	P	80	20
	MP	98	2

Source: Tettenborn (2011)

4.4.1.3 Blackwater treatment

The high organic and solid content of blackwater is ideal for energy and organic fertiliser production that offers more yield than sewage sludge (Wendland et al., 2007). In many studies, anaerobic digestion is introduced as a core process for energy recovery (Lettinga et al. 2001; Kujawa-Roeleveld and Zeeman, 2006; Wendland et al., 2009; Wätzel and Kraft 2014; Sievers, Wätzel, et al. 2016).

Blackwater can be directly connected to the sludge treatment process to produce biogas and organic fertiliser. Since pathogenic micro-organisms contaminate blackwater, it is necessary to consider some pre-treatment like the hygienisation stage (Annex A.9.4) to assure the digester's proper functionality (DWA-A 131). Thermal energy for heating is calculated based on the parameters in Annex A.9.4. When the thermal energy from the biogas combustion is not enough for this process, it is provided by extra fuel into the system. The anaerobic digestion process unit, on the one hand, produces energy in the form of biogas and, on the other hand, requires energy to heat sludge. The heat requirement for sludge heating is dependent on the temperature, volume, and specific heat capacity of sludge and calculated based on the equation (5).

Anaerobic digestion process has been investigated in various types of digesters such as Continuous Stirred-Tank Reactor (CSTR), Accumulation system (AC), an Upflow Anaerobic Sludge Blanket (UASB) with a very extensive range of configurations (see Annex A.9.3 for review of different digester). Table 27 shows the main selected configurations of the digester process unit in this study.

Table 27: The main parameter of digester in this study

Parameter	Value	Unit
Digester type	Mesophilic	-
Digester temperature	38	°C
Retention time	21	day
Biogas production	0.35	m^3 biogas/ kg COD
Percentage of CH_4 in biogas	65	%
Percentage of CO_2 in biogas	35	%

Kujawa-Roeleveld et al., 2003; Otterwasser, 2005; Remy 2010; Tervahauta et al, 2013; Lema and Suarez 2017

The mass balance of anaerobic digestion is considered based on the parameters in Table 28. The degradation process is depended on the organic and solid content that enters the digester and converts it to biogas. The volume of biogas production depends directly on organic matter and solid content. In this study, methane gas production is set in the model to calculate energy production by varying different volumes of primary and excess sludge and based on the production of 0.35 L methane from one g COD equivalent organic under mesophilic condition (Kujawa-Roeleveld et al. 2005; Otter-wasser 2009; Tervahauta 2014; Lema und Suárez 2017). Inorganic nutrients (N, P, K) are not affected by the digestion process (Meinzinger 2010). It leads to a high concentration of nitrogen and phosphorus from sludge liquor rather than sewage sludge that should be treated in a separate treatment process or returned to the mainline of the wastewater treatment process. This section can affect the nutrient recovery from sludge liquor and extra energy demand due to treating the high concentrated sludge liquor in wastewater treatment.

The required electrical energy demand for operating digester is set to 0.003 kWh/kg fresh mass (Remy 2010). The energy balance is estimated according to the energy production from biogas in the digester. This concept considers the thermal energy from incineration a traditional disposal method.

It is assumed the close system of anaerobic digestion does not have emission and emission from sewage gas is considered in CHP plant, and 1% is considered for the possible leakage (Ronchetti et al., 2002; Remy 2010). Cost data for this process unit is presented in Table 29.

Table 28: Functional data of anaerobic digestion process unit

Parameter	Unit	Value	Source
Removal efficiency of COD	%	68	Wriege-Bechtold et al. 2010
Removal efficiency of DM	%	61	"
Removal efficiency of oDM	%	67	"
Biogas production	Lit /g COD	0.35	Kujawa-Roeleveld et al., 2003; Otterwasser, 2005; Remy 2010; Tervahauta et al, 2013
Proportion of methane in biogas	%	0.65	Glizie, 2009
Proportion of CO_2 in biogas	%	0.35	"
Density of methane	kg/m^3	0.72	Remy 2010

Table 29: Cost parameter for anaerobic digester process unit

Parameter	Value	Unit
Digester construction	180	€/pe
Digester equipment	143	€/pe
Digestion O&M construction	1	% Investment
Digestion O&M equipment	3	% Investment
Digester labour	26	€/(pe.a)

1) Meinzinger, 2010 2)Oldenburg and Dlabacs, 2007

*Cost is updated to 2019 based on 3% interest rate

4.4.1.4 Sludge treatment

The excess sludge from the wastewater treatment process can be stabilized by aerobic or anaerobic digestion. Other processes like dewatering and drying can reduce sludge volume and increase the heating value of sludge for incineration. The quality of sludge can be improved by configuration as pre-treatment.

The related processes for sludge treatment can be divided into pre-treatment and post-treatment process units to improve the quality of sludge in reducing the side effect of sludge in the environment.

The equipping of conventional wastewater treatment plants with the anaerobic sludge treatment process has provided the possibility of biogas production from degradable sludge (Mrowiec und Suschka 2005; Gao et al. 2014). Increasing biogas production through anaerobic digestion makes this process more efficient than aerobic digestion and becomes more critical in energy recovery from municipal wastewater (Smith et al., 2012). The anaerobic digestion process is a sustainable option to recover energy while nutrients are preserved for reuse (Jefferson 2019). Therefore, the anaerobic digestion process unit calculates the amount of organic dry matter and volatile solid content for energy production from sludge. The outcome is related to a load of inflow to the digester; therefore, the characteristic of inflow (blackwater or excess sludge from activated sludge) defines various outcomes. Hence, the defined data for anaerobic digestion of sludge produced from mixed wastewater is assumed to be the same as defined data for blackwater treatment (Table 28-29).

Although Solid Retention Time (SRT) and Hydraulic Retention Time (HRT) is playing an essential role in the function of a digester (Zeeman und Kujawa-Roeleveld 2011), due to avoid the complexity in modelling, the retention time is considered constant. The variation is based on the degradable load of influent to the digester.

- Pre-treatment process unit

In order to increase biogas production from conventional mixed wastewater, increasing carbon extraction is a crucial process. This goal can be achieved by increasing the primary sludge by improving the process of settling more primary sludge before digestion. This process is investigated in scenario R3 in this study. Increasing the biodegradability of secondary sludge is feasible by a different hydrolysis method, which in this study, thermal hydrolysis (Scenario R2), is investigated.

Since these processes require extra energy and cost and have their own ecological effect, it has been assessed to identify their impact on these processes.

Extraction of organic matter before biological treatment is considered pre-treatment for anaerobic digestion to increase biogas production. Due to the high degradability of primary sludge, under optimum digestion conditions, a methane yield of 315 – 400 Nm^3/t organic Dry Matter (oDM) can be expected (Zhang 2016). Excess sludge has a smaller degradable fraction than primary sludge and thus a lower biogas yield.

A methane yield of 190 – 240 Nm^3/t oDM can be expected under optimum digestion conditions (Bachmann 2015). In addition, sludge pre-treatment can increase the degradability by thermal, chemical, or biological processes up to 8-30%(Böcker et al., 2005; Remy 2012a).

Thermal hydrolysis is shown to positively impact the dewatering of digested sludge in the post-treatment phase (DWA 2009). Hence, it is assumed that hydrolysis leads to a higher final DM (30%) and less polymer demand in dewatering (9 g/kg DM), and it improves the biogas production by 8% (Remy 2012a). However, liquor from dewatering is loaded with higher concentrations of COD (+50%, COD=2910 mg/L) and N (+25%, (N)=1570 mg/L). Additionally, 43% of COD is assumed to be burning resistance (According to the results in CoDiGreen Project, Remy 2012a).

Once nutrients such as nitrogen and phosphorus are soluble, they are taken during the digestion process or released with the effluent in the dewatering processes. Different studies indicate that some nutrients are lost from sludge during pre-treatment due to the solubilization effect. Consequently, it is expected pre-treated sludge has low nutrient contents compared to untreated sludge (Zhang et al. 2015).

- Post-treatment unit process

Digested sludge contains more than 95% water. Depending on the further application and goal, it can be centrifuged, dewatered, and dried to extract water and reduce sludge volume for appropriate transport. Dewatering and drying are the most common technologies, energy-consuming processes, and the flow contains a significant amount of nutrients and organic. Dewatering can be done mechanically with coagulation agents. The dosage of these polymers is dependent on the final rate of dewaterability (in this study is set to 12g/kg dry matter to reach 27% final dry matter content)(Remy 2012a). By this process, 96% of outflow is directed to sludge liquor, and 4% is directed as a solid phase (Lema und Suárez 2017). The excess sludge liquor must be treated in a sludge liquor treatment process (See section 5.4.5.1). The energy demand and cost for post-treatment processes are in a wide range and significantly depend on the functionality of the applied technique and sludge volume. Tables 30 and 31 show the selected value in this study.

Table 30: Energy demand for conventional sludge treatment and post-treatment processes

Parameter	Unit	Value	Source
Sludge pumping	kWh/kg dry matter sludge	0.01	1
Thickening of raw sludge	kWh/kg dry matter raw sludge	0.03	1
Raw sludge and digester heating	MJ/m³ thickened raw sludge	150	1
Digester with mixing	kWh/kg dry matter raw sludge	0.12	1
Dewatering stabilised sludge	kWh/kg dry matter *	0.06	2
Drying sludge-heating[8]	kWh/m^3	528	3
Drying sludge-electricity	kWh/m^3	53	3
Sludge incineration	m^3 nat. gas/t sludge, 42%DM	20	Mininni et al., 1997

Source: 1) Remy, 2010 based on LfU, 198; Müller et al., 1999; 2) Boehler et al. 2018 3) Remy 2012

*Stablisied sludge

Table 31: Cost parameter for post-treatment processes

Process unit	Parameter	Value*	Unit	Source
Thickening and dewatering	Capital cost	7	€/pe	1
	Operation	247	€/t DM	2
	Maintenance	3	% Investment	2
Drying	Capital cost		€/pe	
	Operation	350	€/t DM	3
	Maintenance	3	% Investment	2

1)Wassmansdorf treatment plant 2016 2)DWA_M_366 (2013) 3)Chip GmbH 2004

*Cost is updated to 2019 based on a 3% interest rate

[8] Energy demand is highly depending on the rate of drying and type of energy. Based on (ATV-DVWK-M 379, 2004) is assumed 70-110 kWh/ tone evaporated H_2O and in the model is recalculated based on m^3 of sludge input to dryer. Remy (2015) is differentiated based on 0.09 kWh/kg evaporated H_2O for electricity and 0.875 kWh/kg evaporated H_2O for heat for sludge drying with 80% TS.

4.4.1.5 Sludge liquor treatment

The returning of the sludge liquor from the digester effluent to the head of the WWTP in the conventional configuration increases up to 15-20% of the nitrogen loading into the treatment cycle (Bachmann 2015) and causes supplementary energy demand for pumping and aeration. The specific energy demand for sludge liquor treatment has been estimated based on extra energy demand for aeration, returning to the treatment process (Table 32).

Table 32: Energy demand for the treatment of return load

Parameter	Unit	Value	Energy demand for aeration kWh/kg O_2	Energy demand for removal
Oxygen demand	kg O_2/kg COD remove	1	0.5	0.50
	kg O_2/kg NH_4-N remove	4.57	0.5	2.29
	kg O_2/kg NO_3-N remove	2.86	0.5	1.43

Source: Remy 2015

Separate treatment of this stream, the so-called "side stream," can reduce nitrogen content by 85-90% (Baumgartner und Parravicini 2018) and thus reduce the load in the biological mainstream treatment. On the other hand, reducing the required volume of the tank in the activated sludge process reflects in the infrastructure and operation cost.

The most applied technologies are the Anammox process and SBR with classical nitrification/ denitrification due to high ammonium concentrate ion, high pH value, and high temperature. The main advantage of Anammox compared to classical nitrification/ denitrification is the absence of emission of unfavourable intermediates and significantly lower costs (Bachmann 2015).

Hence, sludge liquor treatment can lead to the following benefit due to high concentration of nutrients and pollutants:

- Recovers nutrients for beneficial reuse

- Reduced the N/P loading to liquid treatment line by less power/ smaller carbon footprint, more stable operation, the higher safety factor for the operation of treatment

- Reduced volume/ nutrient content bio-solids

According to many studies, although the nitritation and Anammox process is an efficient and cost-effective approach for biological nitrogen removal, the operation of these processes requires a high level of maintenance and thus additional costs. In case of operation without any disturbances, higher costs due to the accuracy of the measurement (control the accurate range of pH) can be expected. Additionally, qualified and trained personnel can increase operating costs.

The efficiency of the deammonification is assumed to be 86% N removal. 11% of the input N load to deammonification is emitted as NO_3, and it is recycled back to the WWTP, which avoids additional energy demand in the mainstream. The energy demand is considered 1,3 kWh/kg N_{elim}. N_2O emission from the deammonification process can be higher than from mainstream nitrification/denitrification. For this study, the emission factor of 23 gN_2O-N/kg N inflow is assumed as an average based on the Biere et al. 2008 study (Remy 2012a).

The emission factor of sludge is estimated for N_2O, with specific emission factors. N_2O emission factor for large-scale WWTPs with nitrification-denitrification can vary over a wide range (0-25,3% of eliminated N load) (Kampschreur et al. 2008; Ahn et al. 2010; Foley et al. 2010). Low oxygen levels in nitrification, increased N_2O concentration, low COD/N ratio in denitrification is influenced the N_2O release. The emission factor of 6 g N_2O/kg N_{elim} is estimated according to the mean value of screening of 25 German WWTPs (Remy 2012a).

4.5 Process unit for water, energy, and nutrient recovery

Process units in the recovery step include the processes which lead to recover energy and nutrients from treatment processes. Critical technologies for nutrient and energy recovery of the conventional and source-separated system are considered to evaluate the impact of recovery process units (Table 33).

Table 33: Overview of process units in recovery functional group

Sanitation concept	**Flow type**	**Process type**	**Recovery type**
Conventional	Mixed wastewater	Conventional wastewater treatment	Water recovery
		Struvite	P recovery
		Stripping	N recovery
		CHP	Energy recovery
Source separated	Blackwater	CHP	Energy recovery
		Struvite	P recovery
	Brown water		
	Urine		N recovery
		Stripping	

Various recovery processes for conventional and source-separated concepts exist. In recent years, some European research and demonstration projects (P-Rex, Co-DiGreen, POWERSTEP, PHORWÄRTS) have focused on recovery from the conventional sanitation processes.

However, most of these technologies are not yet cost-effective; therefore, they are not applied to large-scale plants.

Valuable resources can be recovered from sewage sludge within the following processes:

- Energy recovery by combustion of biogas in a Combined Heat and Power (CHP) plant which recovers energy - electrical and thermal

- Energy recovery from combustion of dewatered or dried sludge in incineration[9]

- Nutrient recovery by struvite precipitation from sludge liquor which can be applied as fertiliser with phosphorus and nitrogen content

In the context of this study, the technologies applied or investigated for recovery from mixed wastewater are also set up to assess the potential of recovery from different source-separated flows. Recovery from source-separated wastewater allows focusing on each type of flow based on their potential. According to the configuration of the developed tool, when the high concentrated flows like blackwater and yellow water are charged into a process unit, the various aspects of sustainability will be calculated based on the load of the flow. Consequently, it is expected that biogas production is increased significantly for the blackwater, which has more organic carbon concentration than mixed wastewater. Consequently, the other important criteria in terms of sustainability are considered.

The recovery process units for source-separated flows have the same framework as mixed wastewater to provide the same scale of comparison and focus on the energy and nutrient recovery based on the higher or less load of material defined for each unit.

4.5.1 Energy recovery

CHP technology by transferring biogas to electrical and thermal energy provided some portion of energy requirement in the treatment process. It has been improved since last years, and the efficiency has been significantly increased to produce electrical energy (Bachmann, 2018). Table 34 indicates the functional parameter of CHP in different configurations, and Table 35 shows the related cost data.

Biogas has an energy content of about 6.3 kWh/m^3, depending on methane concentration (Thomé-Kozmiensky, 1995; Köttner, 2005), which can substitute the part of the energy requirement the digester (Peters, 2002; Wendland, 2008).

[9] Incineration is out of defined boundary condition in this study and only the indirect effect of this process is taken to consider

Table 34: Functional parameters for CHP

Parameter		Value	Unit	Reference
Energy production	Thermal	4	kWh/m^3 Biogas	Remy, 2010
	Electrical	2	kWh/m^3 Biogas	
Electrical efficiency*	1-30 kW	30	%	DWA-A 216, 2015 based on ASUE, 2014
	30-50kW	32-35	%	
	50-100 kW	35-39	%	
	100-250 kW	39-40	%	
	>250	40-43	%	
Thermal efficiency*	1-30 kW	54-70	%	
	30-50kW	47-55	%	
	50-100 kW	43-55	%	
	100-250 kW	40-54	%	
	>250	40-52	%	
Emission	CH_4	9.26	mg/kWh	Remy, 2010; Ronchett, 2002
	CO_2 non-biogenic	301.15	mg/kWh	
	NO_2	140.74	mg/kWh	
	N_2O	5.93	mg/kWh	
	CO	188.89	mg/kWh	
	SO_2	111.11	mg/kWh	
Energy demand	For gas purification	0.04	kWh/m^3 Biogas	Remy, 2012
	Operation	0.096	kWh/m^3 Biogas	

* Based on Gas-Otto engine selected from DWA -A 216 DWA

Table 35: Cost parameters for energy recovery units

Process unit	Parameter	Value*	Unit	Source
Energy recovery -CHP	Investment cost	16	€/pe	1
	Operation	2	% Investment	2
	Maintenance	2	% Investment	3

1) Wansdorf, 2011 2)Steurer, Haasz et al. 2017 3) Meinzinger, 2010
*Cost is updated to 2019 based on a 3% interest rate
*Data is extracted from GK5

The incineration process does not belong to the sanitation system, but excess sludge is directed to the incineration plant to burn out. Therefore, the energy gained from burning is considered as recovered energy.

Since the self-sustained incineration can be operated with the low heating value of solid 4 MJ/kg (Waschnewski 2010, Remy 2012), and dewatered sludge due to the water content has 2.2 MJ/kg low heating value. Therefore, the incineration process requires additional fuel for incineration.

The drying process with intensive energy demand improves the dry matter content and decreases water content. The dewatered sludge is either dried on-site and then transported to the incineration plant or directly transported to the incineration plant and dried at the site.

The generated energy by incineration process is 620 kWh/t dry matter (Waschnewski 2010) by using a waste heat boiler and condensing turbines.

Based on the lower heating value of input sludge, the efficiency of generated energy is assumed 14% of electricity, 73% of heat. The electricity demand of the incinerator is estimated at 0.23 kWh/kg DM (Remy, 2015). Process data for the incineration plant in terms of material and energy demand provided based on Outotec as available technology. After the off-gas cleaning process, decisive emission gas is the emission of SO_2 61 mg and 15 mg per kg DM input, and N_2O emission from fluidized bed incinerator are assumed 990 mg/kg DM (IPCC (2006)) by 900°C freeboard temperature of the incinerator. The remaining volatile solids in sludge and nitrogen is oxidized completely during incineration, and heavy metals and phosphorus are bound in the ash. Since the incineration plant is not a part of the wastewater treatment process, only cost data is taken to consider, which influences cost analysis in wastewater treatment plant processes. Table 36 shows the cost of each route.

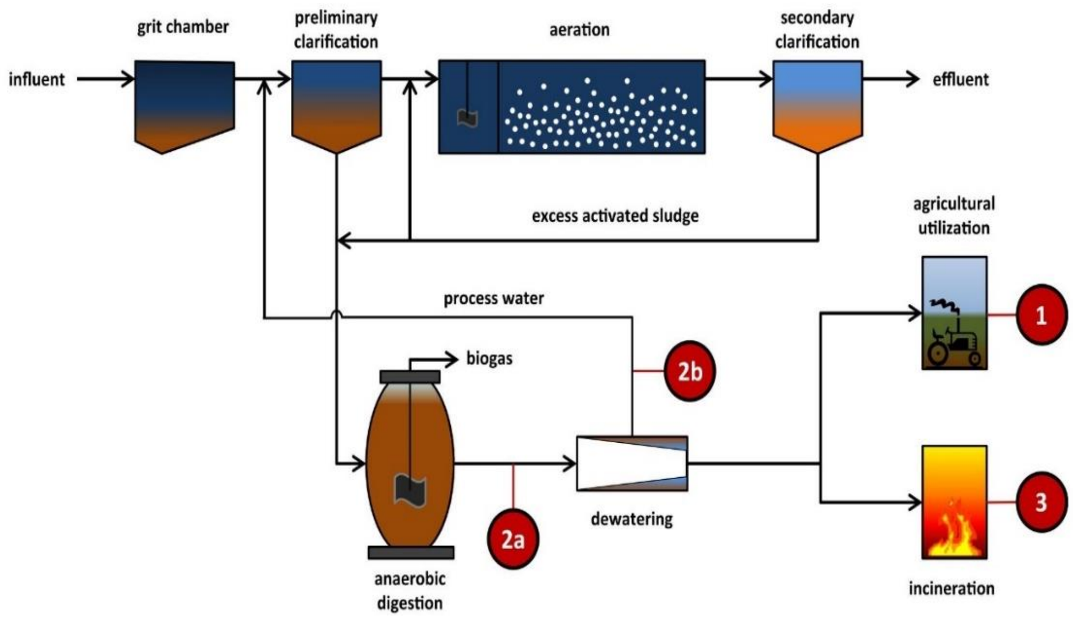
Table 36: Cost for different options of incineration

Process	Value	
	€/(pe.a)	€/ t DM
Mono-incineration	6.84	380
Thermal drying and incineration	5.22	290
Solar drying and incineration	5.67	315
Dewatered and co-incineration	6.12	340

Source: Roskosch et al., 2018
Based on the average value for Germany and assumption of wastewater production: 55 $m^3/(pe.a)$ wastewater fee: 2.2 €/m^3 and sewage sludge rate: 18 kg DM/(pe.a)

4.5.2 Nutrient recovery

Depending on the infrastructure for wastewater treatment, nutrients (specifically phosphorous) can be technically recovered from the liquid phase of sludge or after the dewatering process. If sludge is incinerated in mono-incineration plants, the remaining products are rich in phosphorous concentrate but, due to the minimal plant availability of the nutrient in ash, further treatment is required (Adam et al. 2009; Steinmetz et al. 2013; Kabbe 2013; Schoumans et al. 2015; Kraus et al. 2019). Figure 22 shows the possible routes for nutrient recovery from conventional sanitation systems.



Source: (Schoumans et al. 2015)

Figure 22: Phosphorus recovery options

An overview of 20 different processes of phosphorous recovery facilities in Europe, which have been already implemented in full scale, is shown in Annex A.10.1. According to this overview, crystallization of struvite tends to be favoured by providing a slow release of fertiliser with excellent plant availability. Crystallizing struvite directly after digestion and prior to dewatering led to increased recovery efficiency and dramatically decreased operational cost (Berlin Wassmannsdorf, 2013) even without selling the struvite. Reduced sludge disposal costs obtain these benefits due to improved dewatering, less chemical use, and lower maintenance costs for pipe clogging and abrasion of the centrifuge. Although most of the implemented nutrient recovery methods show benefits, these technologies are mostly limited to WWTP with biological phosphorus removal.

P- recovery can be achieved in a range of 4-18% of total P in sludge with a relatively low effort in energy and chemical use. P recovery up to 98% with the thermo-chemical treatment of ash is possible with high energy demand or chemical use. However, the product still contains high amounts of heavy metals, and further treatment is required to decrease environmental impacts (Remy, 2015)[10]. The content of heavy metals and organic pollutants is one of the main discussions in the P recovery, which should be considered. For most processes, the mass

[10] The detailed explanation of these processes can be found in the report "Sustainable sewage management fostering by Kompetence Wasser Berlin (2015) and PHORWÄRTS (2019).

balance of heavy metals could not be derived from the existing data. Therefore, in this study, the mass balance of heavy metals is not implemented in the modelling process.

In this study, the N recovery process is considered for highly concentrated flow, mainly in source-separated scenarios (Urine treatment). Steam or air stripping is available for nitrogen recovery (Maurer et al., 2006; Tettenborn et al., 2007; Lema und Suárez 2017).

Data for process modelling is mainly collected from European research and demonstration projects which are about to evaluate different recovery processes and resulting products and their LCA analysis (Kabbe 2013; Schoumans, 2015; Remy 2015; Kraus et al. 2019) (Annex A.10.2 and A.10.3 shows the functional parameter which is adopted from this study and it sets for the modelling processes). Table 37 shows the main data process which is applied for creating scenarios in this study. The content of nutrients in each product from the recovery process is calculated based on the molar mass of the product.

Table 37: Functional parameters of P recovery from different flows

Process unit	Product	P recovery rate [1]	Chemical demand	Energy demand [2]
Sludge	Struvite	5-15%	$MgCl_2$ (30%)3.4 lit/m^3	0.92 kWh/m³
Sludge liquor	Struvite	5-40%	$MgCl_2$ (30%)1.3 lit/m^3	0.36 kWh/m³
Ash	H_3PO_4	>80%	$Ca(OH)_2$ (100%) 0.26 lit/m^3 H_2SO_4 (78%) 0.28 lit/m^3 NaOH (50%) 0.05 lit/m^3	-

Source: Remy 2015, Kraus et al. 2019
1 related to total P load in raw sludge (= 100%)
2 related to input flow (sludge or liquor)

The mass balance in the recovery unit is more complicated than the definition of removal efficiency of the process unit, and it is affected by molar mass. Phosphor precipitation happens based on the dissolved P inflow, and the biological or chemical P removal plays an essential role in selecting the method. Therefore, the setting of chemical or biological P in the wastewater treatment process unit is considered in the model. Mass flow of struvite is assumed 8 kg per kg of phosphor inflow based on struvite molar mass. Nitrogen content is calculated based on 0.45 kg N per P content in struvite. NH_3 solution with 41% of $(NH_4)_2SO_4$ is considered based on 12 kg/kg N removed. (Haberkern et al., 2008; Dockhorn 2007a; Meinzinger 2010)

There is no published information regarding the direct emission during P recovery and the indirect emission regarding the application of the product as fertiliser. Hence, the emission from the recovered nutrient from the wastewater flow is calculated based on substituting these products with mineral fertiliser. The amount of emission for those applications is discussed in section credit for substitution (Section 4.6.2).

Since the cost for the recovery process units are mostly related to the small pilot plants and are not published; In the framework of this study, the investment cost is estimated based on the set up of available sources and most operators, and it has referred to population equivalent. Table 38 shows the defined cost for each process unit in this study. Regarding the decreasing of investment cost by the larger pilot plant, 30% is assumed for plausible value. It is assumed that 50% of the costs are related to machinery and electrical equipment with 12.5 years lifespan, and the rest is related to construction with 50 years lifespan. Operation and maintenance, including labour and repair, is assumed 4% of the investment cost. The other energy and chemical demand costs are set as a running cost and listed in Annex A.8.

Table 38: Cost parameter for nutrient recovery process units

Process unit	Parameter	Value	Unit	Source
P recovery-AirPrex	Investment cost	5.5	€/pe	1
	Operation	1	% Investment	1
	Maintenance	3	% Investment	1
N recovery-Steam stripping	Investment cost	0.7	€/m³	2
	Operation	1	% Investment	2
	Maintenance	2	% Investment	2

1) Ortwein 2016 – AirPrex® 2) Meinzinger, 2010

*Cost is updated to 2019 based on a 3% interest rate
*Data is extracted from GK5

4.6 Process unit for disposal/application

The process unit for disposal and application is presented to evaluate the benefit of recovered energy, nutrient, and water from wastewater treatment processes. The produced energy by CHP plant and incineration is assumed to be substituted by grid electricity, and recovered nutrient (mostly P recovered) is counterbalanced as organic fertiliser[11] with mineral fertiliser. The end product and by-products from different wastewater treatment processes are accounted as credits.

The credit describes the direct benefit of recovered energy and nutrient and indirect benefits by saving energy demand from grid electricity, loss of heating energy, and decreasing the amount of ash disposal. In order to calculate the credits in this process unit, the proposed method by Curran (2007) is used to calculate the environmental impacts of substituted products of fossil fuel, fertiliser, and energy production.

[11] In the context of this study, organic fertilizer is the recovered nutrients which can be used as a fertilizer

4.6.1 Credit for substituted energy

Energy demand in the form of electricity and heat in different wastewater processes leads to emission, according to Table 39. By substituting generated energy from CHP and incineration, these amounts of emission can be considered a credit.

Table 39: Substitute of emission factor by energy recovery

Parameter	Unit	CO_2-eq emission
Electricity	kg/kWh	0.563
Heat	kg/kWh	0.251

Source: DWA-KA1.6, 2017

4.6.2 Credit for substituted nutrients

Substitution of mineral fertiliser with the recovered nutrient of wastewater is one of the main applications of the product of wastewater. Direct application of stabilized sludge in agriculture is the traditional path to close the loop of nutrients. However, regarding the increased concern about the pollutants (heavy metals, organic pollutants, and pathogens), this route is restricted and even banned in some countries (e.g., Switzerland, Germany in the future). Considering the restriction for the application of sewage sludge in agriculture based on the legislative framework in Germany fertilizing ordinance (DüV 2017) and sludge ordinance (Klärschlammverordnung, AbfKlärV 2017), the direct application of sewage sludge is not considered in this study and only the by-product of nutrient recovery (like struvite or liquid fertiliser) is taken to consider. More detailed information regarding the direct application of sewage sludge can be found in the SCST project (Peter- Frölich et al., 2007) and the LCA study by Remy (2010).

In general, applying anaerobic digestion output in agriculture and releasing them to the environment typically requires post-treatment for removing pathogens and remaining organic matters and micropollutants according to local legislation (Kujawa and Zeeman, 2006; De Graff et al. 2010).

In order to evaluate the effect of substituting organic fertiliser with mineral fertiliser, the production of mineral fertiliser and the associated emission and energy are considered. Table 40 shows the energy supply, emission, and transport from the natural resources until the packing of the marketable product. This evaluation allows quantifying the emission and energy saved by substituting organic with mineral fertiliser.

Table 40: Energy and emission from mineral fertiliser production

Parameter		Unit	Kg N	kg P_2O_5*	Source **
primary energy demand		MJ	48.896	17.432	1
Emission (Air)	CO_2 (fossil)	kg	2.82	1.117	1
	CH_4	kg	0.00745	0.00207	
	NH_3	kg	0.00669	0.00001	
	N_2O	kg	0.01505	0.00004	
	NO_x	kg	0.01576	0.00858	
Emission (Water)	NH_3-N	kg	0.00268	0.00917	2
	NO_3	kg	0.0189	0.00816	
	PO_4	kg	0.02862	4.4	

1)Patyk and Reinhardt, 1997

2)Gaillard et al., 1997

*In order to convert P_2O_5 to P is divided to 2.29

**Data is adapted by Remy 2010

The existing datasets for the environmental impact of mineral fertiliser production are originated from the 1990s (Patyk und Reinhardt 1999). Probably, due to the changes of technologies in mining processes over the last decades, those data are not reflecting the accurate environmental impact of these processes. However, updated datasets are not publicly available; therefore, the environmental impact of substituting mineral fertiliser with organic fertiliser might be overestimated.

Organic fertilisers such as stabilised urine, struvite, or liquid fertilisers caused nitrogen emission. Whereas mineral fertiliser is offered as solid, stable chemicals without the potential for greenhouse gas emission, however, during the application, emissions may be caused by different forms of nitrogen (NH_3, N_2O, and NO_x). In this study, the possible emission from P fertiliser is neglected due to the small amount of these gases. Table 41 presents the emission from fertiliser.

Table 41: Emission from mineral and organic fertiliser

Parameter	NH_3	N_2O	NO_x	$CO_{2\ fossil}$	Source
	kg NH_3-N/kg N	kg N_2O-N/kg N	kg NO_x-N/kg N	kg CO_2/kg N	
Mineral fertiliser	0.05	0.0125	0.007	0.59	1.2
Sewage sludge	0.08	0.0125	0.007	0	3
Urine	0.1	0.0125	0.007	0	4
Stabilised digester residual	0.063	0.0125	0.007	0	3
Liquid digester residual	0.22	0.0125	0.007	0	2.3

1) ECETOC, 1994 2)EMEP/CORINAIR, 2004 3) Remy,2010 4) Muskolus, 2008

In general, the emission from fertiliser significantly depends on the application method on the field, soil type, and condition (pH, infiltration), weather condition (precipitation, temperature) (ECETOC 1994). Therefore, it has been proposed to estimate on-field nitrogen emission in literature. Therefore, the constant factor is adapted from LCA studies and emission inventory (Remy, 2010).

Mineral fertiliser is supplied so that the plant uses the total amount of nutrients in a short time. Hence, they can be applied precisely during the plant's growing period to provide the nutritional demand of crops.

The plant availability of nutrients from digester residuals significantly depends on the post-treatment. When the digester residual is dewatered, a large part of inorganic nitrogen is lost with leachate or atmospheric emissions. According to estimation in literature, only 30% of the nitrogen can be taken by plants (Roschke, 2003; Remy, 2010). Part of phosphorus and potassium is lost by leachate, but the main part of phosphorous remains on stabilized digester residuals. In addition, the plant availability of Phosphorous mainly depends on the mode of phosphorous elimination in the wastewater treatment processes. In contrast, chemical P removal results in a substantial fixation of phosphorous with precipitants and limits availability for plants (Schönberg et al., 2018). However, Phosphorous from biological P removal is entirely available for plants.

In order to reflect the effective potential of organic fertiliser from wastewater processes to substitute mineral fertiliser, the plant availability of the nutrients from organic fertiliser must be considered. Due to the specific biogeochemical cycle of each nutrient for plant availability, the relative nutrient availability is estimated based on the pilot studies and literature review (Table 42). The potential uptake of nitrogen depends on the percentage of inorganic nitrogen, so the mineralization of nitrogen (transformation of organic to inorganic nitrogen) plays an essential role in nutrient plant availability. This transformation is done through the various biological process in soil. The chemical equilibriums and dissolution kinetics determine phosphorous and potassium availability for the plant. Plants can only take them in soluble form and inorganic (Remy, 2010).

Table 42: Potential nutrient uptake from organic fertiliser

Parameter	Nitrogen	Phosphorus	Potassium
	% of N total	%of P total	% of total K
Sewage sludge	50	70	100
Urine	100	100	100
Stabilised digester residual	30	100	100
Liquid digester residual	90	100	100

Source: see Annex A4

In order to calculate the economic benefit of each process unit, a revenue of possible products is shown in Table 43.

Table 43: Monetary benefit from recovered energy and nutrients

Parameter	Value	Unit	Source
Benefit from biogas	0.11	€/kWh	BMU, 2009
Benefit from NH4-solution	82.7	€/t N	Herbst, 2008; Dockhorn,2007
Benefit from MAP	2076.4	€/t P	Herbst, 2008; Montag, 2008; Wilsenach, 2006
Benefit from MAP $_{Urine}$	5652.5	€/t P	Esemen and Dockhorn, 2009
Urine steam stripping	1354.5	€/t N	Dockhorn,2007
Application urine, slurry	3. 8	€/m^3	fbr, 2005

*Cost is updated to 2019 based on a 3% interest rate

Source: Meinzinger, 2010

5 Results and discussion

5.1 Energy demand for operation

Figure 23 shows the specific energy demand for each investigated scenario and the recovered energy gained through biogas combustion and incineration. The negative value presents the energy that can be recovered through different processes. The net value of energy from heat[12] and electricity for each scenario is also shown. Net energy indicates the total energy demand for each scenario after considering replacing the recovered energy with the total energy demand.

The main source of energy demand is in the form of electricity and heat. Hence, the recovered energy is considered in these two forms. It should be taken into consideration that the main part of the recovered energy (more than 70%) is in the form of heat energy which can be used locally or to connect to a heat network by district heating system; otherwise, it should be considered as an energy loss. Two different net energy values are presented since the recovered heat are assumed to be used only locally. Net electrical energy shows the total energy by substituting electrical recovered energy. Net heat and electricity energy show total energy balance potential by considering both electricity and heat energy.

Comparison of net electrical energy shows the highest value of 38.64 kWh/pe.a in scenario separation of greywater (S1) and the lowest value of 15.40 kWh/pe.a by scenario enhancement of primary sludge production (R3). However, considering the net heat and electricity energy, the separation scenario of black, urine, and greywater (S3) shows the highest value.

In order to explain the reason for these values, a detailed contribution of energy demand and energy recovery based on involved processes is presented respectively in figure (24) and (25).

Scenario S1 in figure 24 shows the 12 kWh/pe.a for dewatering and 13 kWh/pe.a for anaerobic digestion) as main contributors to energy demand, which is 24% more than the total energy demand in the reference scenario. It has occurred because the blackwater from the vacuum toilet is directly flowing to the digester, and it causes more volume of inflow compared to other scenarios. This is also shown in vacuum scenarios in Remy's study (2010) with 40% and Meinzinger's (2010) for 4CODig scenario with a 7% increase compared to the reference scenario of these studies.

Scenario R3 with the enhancement of primary sludge production generates 20% more recovered energy through biogas production than the reference scenario (R0) by entering more degradable organic matter into the digester. Although the biogas production in scenario S1 is relatively as high as scenario R3, as it is mentioned, the high energy demand in anaerobic digestion and dewatering offset the recovered energy.

[12] The produced heat energy in this study is assumed to come from organic matter through digestion and incineration process. The other potential of heat energy (e.g., heat recovery from greywater) is not considered.

As shown in Figure 24, a significant part of energy demand in scenarios R0 to R6, where wastewater is mixed from source and flows to wastewater treatment, occurs in secondary treatment and decreases in source separation scenarios S1 to S3, respectively 22 to 57%. On the other side, the main energy demand in the source separation scenario belongs to the energy-intensive process for the nutrient recovery process. In scenarios S2 and S3, a significant part (20 kWh/(pe.a)) of energy is due to steam stripping. Scenario S1 shows the highest energy demand coming from energy demand for the sludge treatment process.

The generated biogas and incineration are the main sources for accounting for the recovered energy from the wastewater treatment process. As Figure 25 shows, in scenarios R0 to R3, co-incineration is considered a process for sludge disposal, and sludge is co-incinerated in cement and lignite power plant to replace part of energy demand. Although these scenarios indicate the substitution of energy demand, co-incineration has a limited application in Germany (Wiechmann et al., 2013). Therefore, mono-incineration in scenario R4 is considered for energy recovery. It is also considered for the source separation concept. Comparison of reference scenario (R0) with Scenario (R4) where only mono-incineration is selected as a disposal route shows the reduction of recovered energy to 50% (see Figure 24). This recovered energy is generated mainly from biogas combustion with -22.14 kWh/pe.a and the rest from mono-incineration with -11 kWh/pe.a. The distribution of the recovered electricity and heat is shown in Figure 25.

In source separation scenario S1, the recovered energy has increased to 12% compared to the conventional scenario of R4 due to the concentration of organic matter from blackwater in the digester. It should also mention that incineration is not a part of the wastewater and sludge treatment process beyond the defined boundary condition. It is only considered for calculating the potential of energy recovery from sludge in the energy life cycle.

Comparing the reference scenario with other scenarios based on net recovery shows that the potential of recovered energy in scenarios R1 to R3 is considerably high due to the calculation of the potential of combustion of organic dry matter in co-incineration. Therefore, the net heat and electricity values are in the range of -31 to 42.80 kWh/pe.a which means the recovered energy from whole processes. However, it will not take place in Germany due to the other environmental consideration. Scenario R4, considering mono-incineration, shows relatively more minor net than the reference scenario (7% for net electrical and 118% for net heat and electricity lower). Scenarios R5 and R6 focusing on nutrient recovery from mixed wastewater show a similar range of net energy. Source separation scenarios present significantly 50% more net energy than scenario R4. It is mainly due to the high energy demand for nutrient recovery processes.

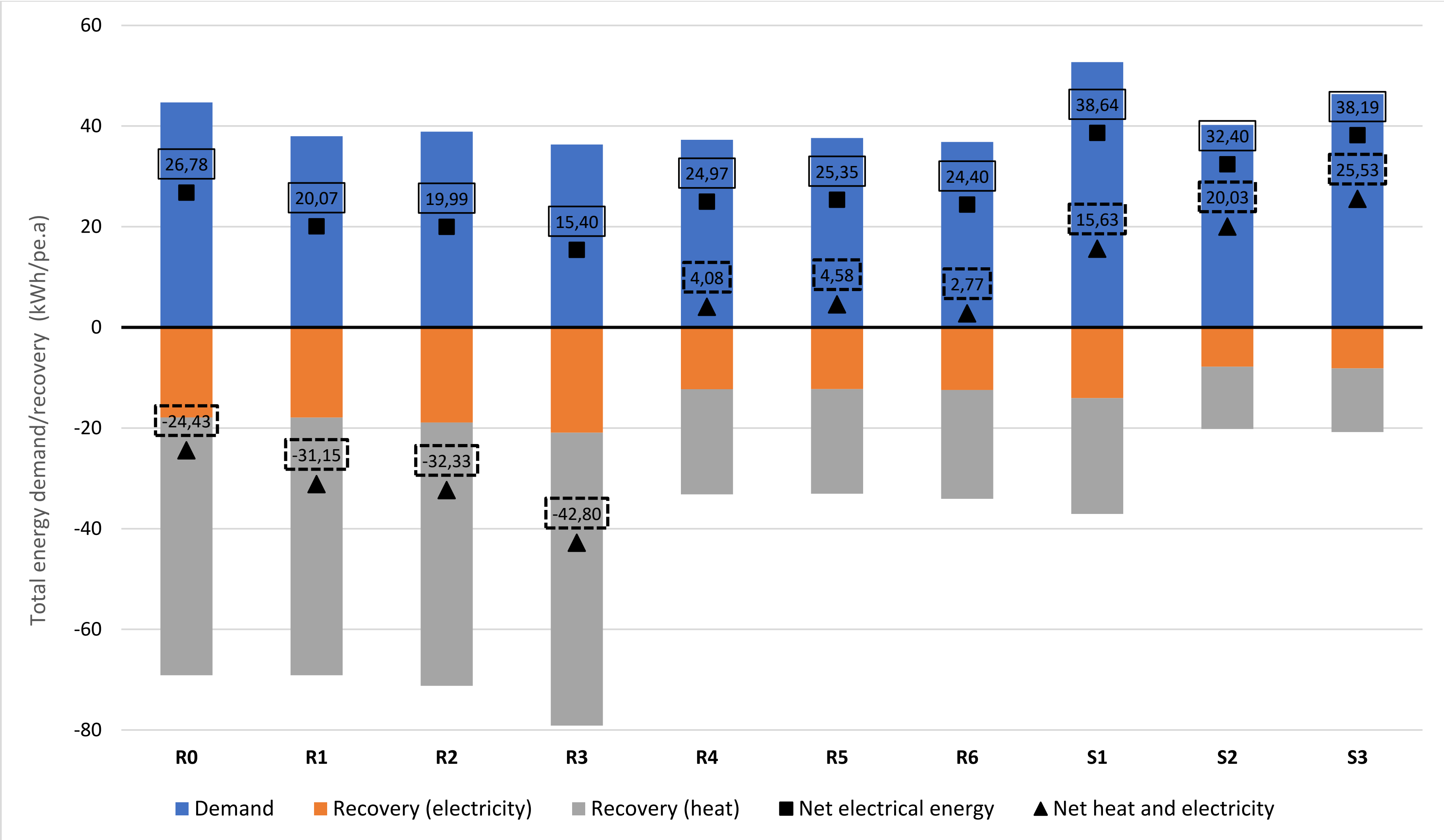


Figure 23: Total net energy demand

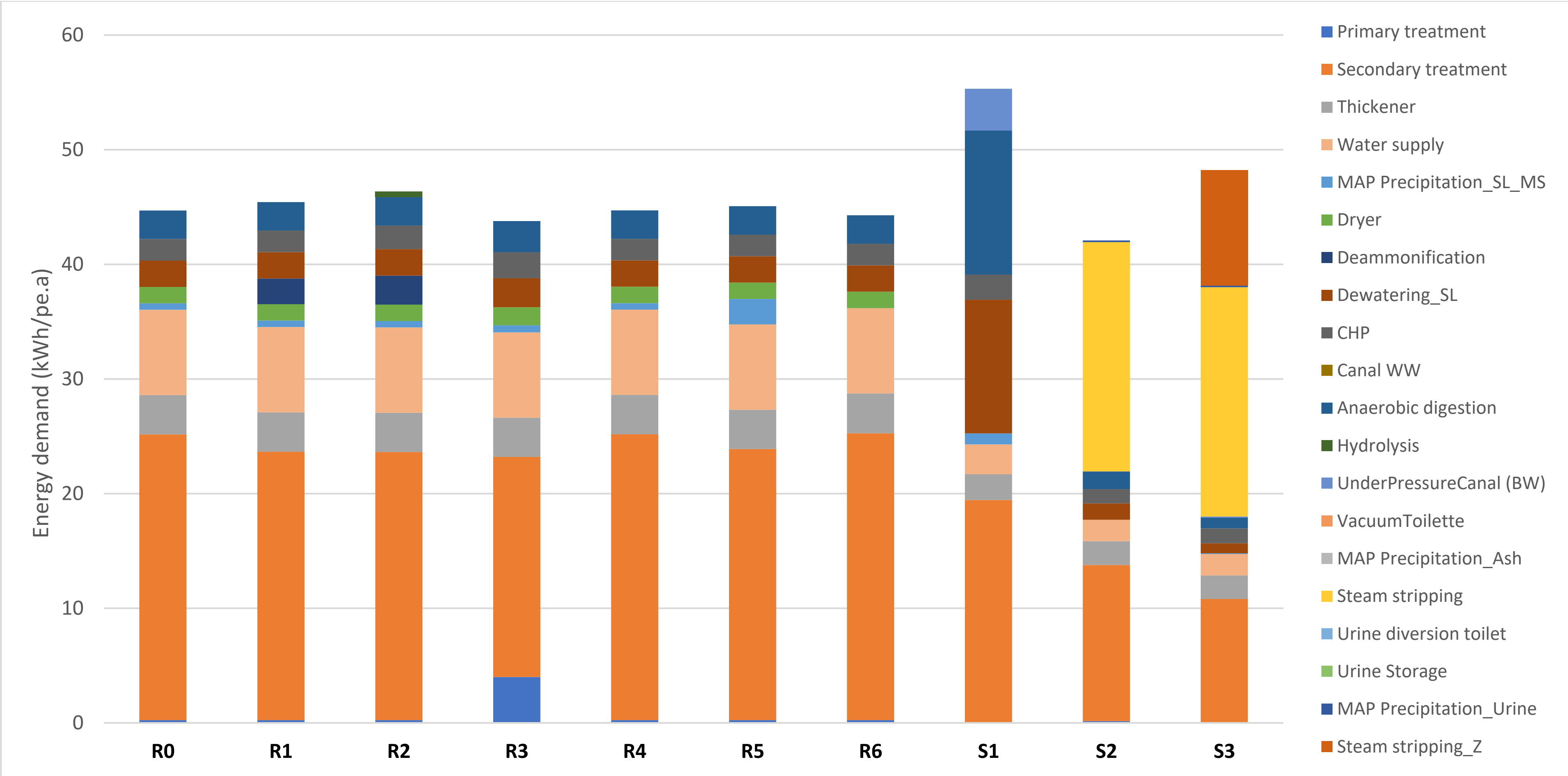


Figure 24: Total energy demand

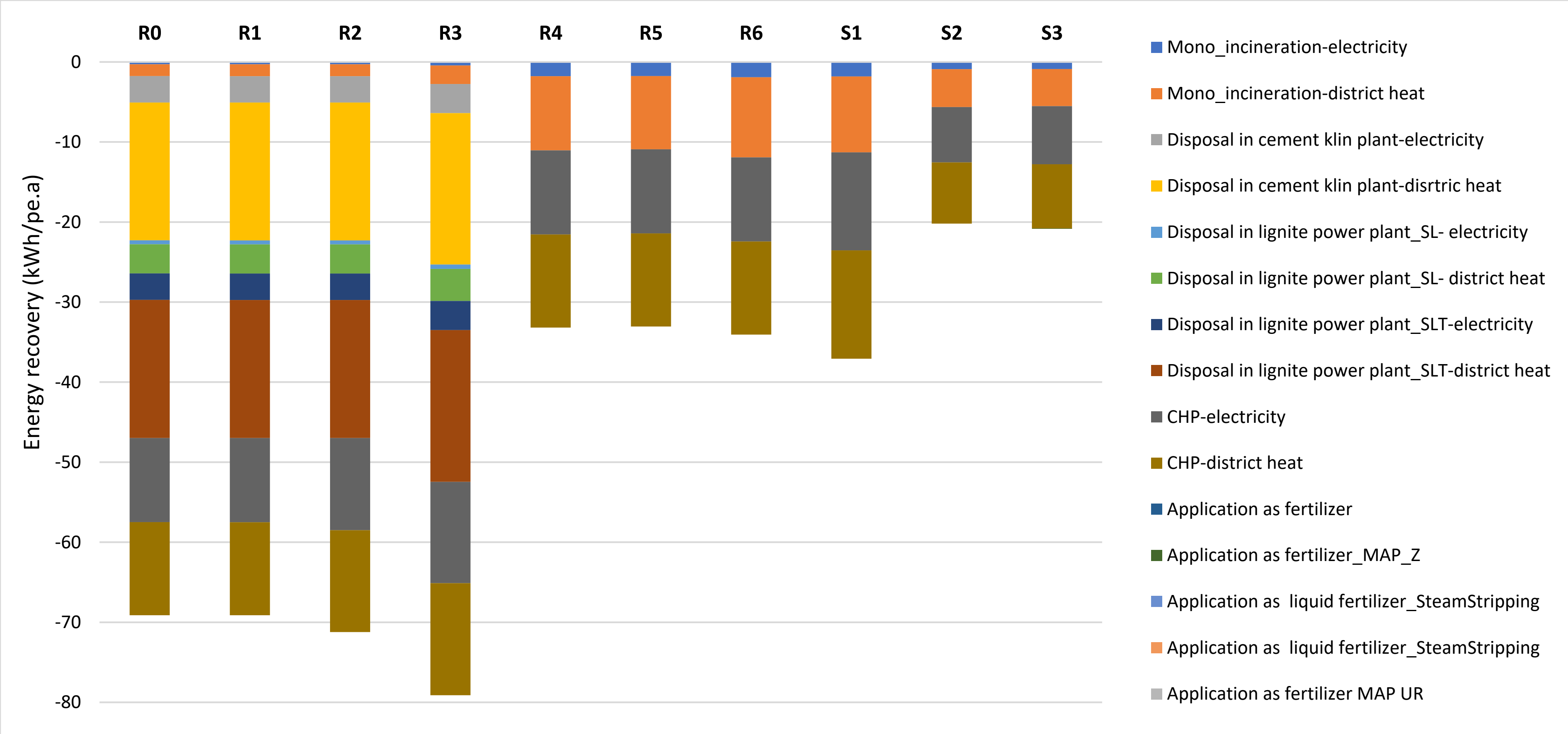


Figure 25: Total energy recovery including process outside of boundary condition

5.1.1 Cumulative energy demand

In order to equivalent the required energy for the related processes for nutrient recovery and transport, the cumulative energy demand of different processes is investigated. The total cumulative energy demand indicator quantifies the amount of energy demand from different sources (electricity, heat, fossil fuel) based on life cycle inventory for a life cycle of 100 years.

The contribution of different processes for each scenario is shown in Figure 26. The net value compares the total energy by considering the recovered energy through different processes.

Scenario S1, with the highest net value of 91.13 MJ/(pe.a), indicated that the separation of greywater and high concentration of blackwater increased recovered energy by the convention of organic matter to biogas. However, this scenario does not offer gained energy due to the high demand for anaerobic digestion and dewatering.

The lowest net energy by R3 with the enhancement of primary sludge production reveals the increase of recovered energy by co-incineration and extraction of degradable carbon via advanced primary treatment.

The highest and lowest net energy value shows the same pattern, which is shown in the energy analysis in Figures 24 and 25. The difference is the effect of recovered energy gained by substituting recovered nutrients with fertiliser. As it shows in Figure 26, source separation scenarios S2 and S3 have negative net energy values where fertiliser substitution formed 50% of recovered energy. The benefit of recovered energy from the conventional concept with nutrient recovery (scenario R5 and R6) shows 18% of recovered energy in this scenario.

In general, the contribution analysis of cumulative energy demand indicates that the supply of equivalent products significantly impacts the net energy comparison of source separation and conventional concepts.

Although the infrastructure of source separation significantly influences the cumulative energy demand in terms of separated piping systems in house and sewer systems (Remy, Oldenburg, Meinzinger), this effect is not investigated in this study. This study aims to calculate the energy balance in terms of substitute of energy demand with the recovered energy and nutrient and substitute with fossil fuel and fertiliser.

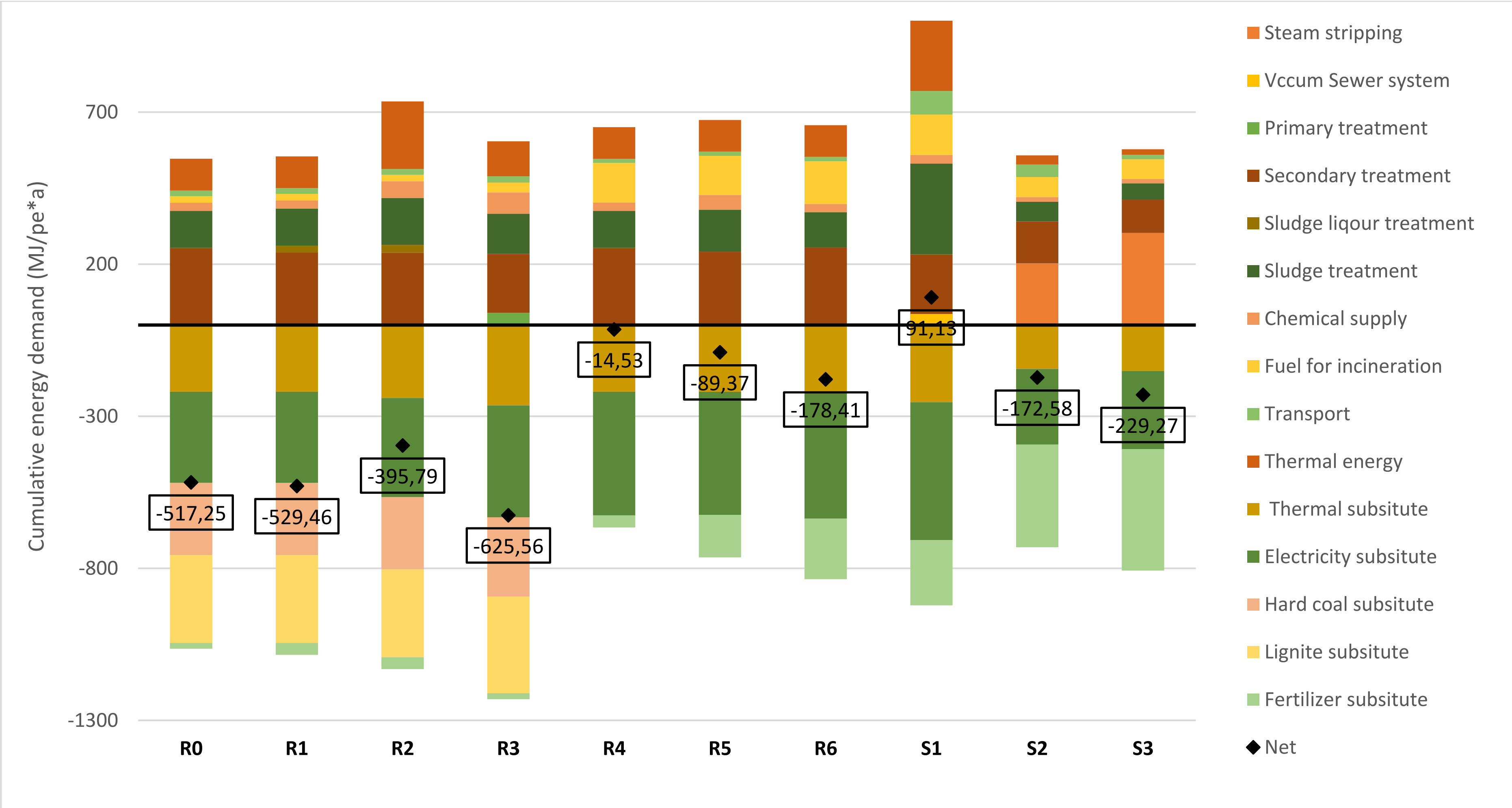


Figure 26: Cumulative energy demand of defined scenarios

5.2 Emission of nutrients to the environment

5.2.1 Emission to water: COD, P, N

Nutrient emission to surface water, soil/groundwater, and air have an essential effect on the pollution of the environment, global warming, acidification, and eutrophication. Hence the essential nutrients are presented based on the following:

The effluent concentration reaching the water resource process unit is considered for assessing the emission to the water of each scenario by comparing the scenarios (Figure 27-29) with the COD, N, and P based on the legal discharge limits in Germany (AbwV 2018).

All calculated effluent concentrations of all scenarios are between 14-33 g/m^3 COD and fulfil the legal discharge limit of 75 g/m^3 for the size category 5, >100,000 PE. According to wastewater ordinance, Annex 1 in Germany, two parameters of nitrogen (NH_4-N and N_{total}) are regulated for the nitrogen content of the effluent. The limit for ammonium nitrogen is 10 g/m^3 and for total nitrogen 13 g/m^3. In all scenarios, the concentration is below 10 g/m^3; in scenarios S2 and S3, the amount of nitrogen is significantly decreased due to nitrogen recovery by steam stripping.

P_{total} concentration in effluent also fulfils the legal discharge with less than 1 g/m^3 for the size category 5 for all scenarios (Figure 29).

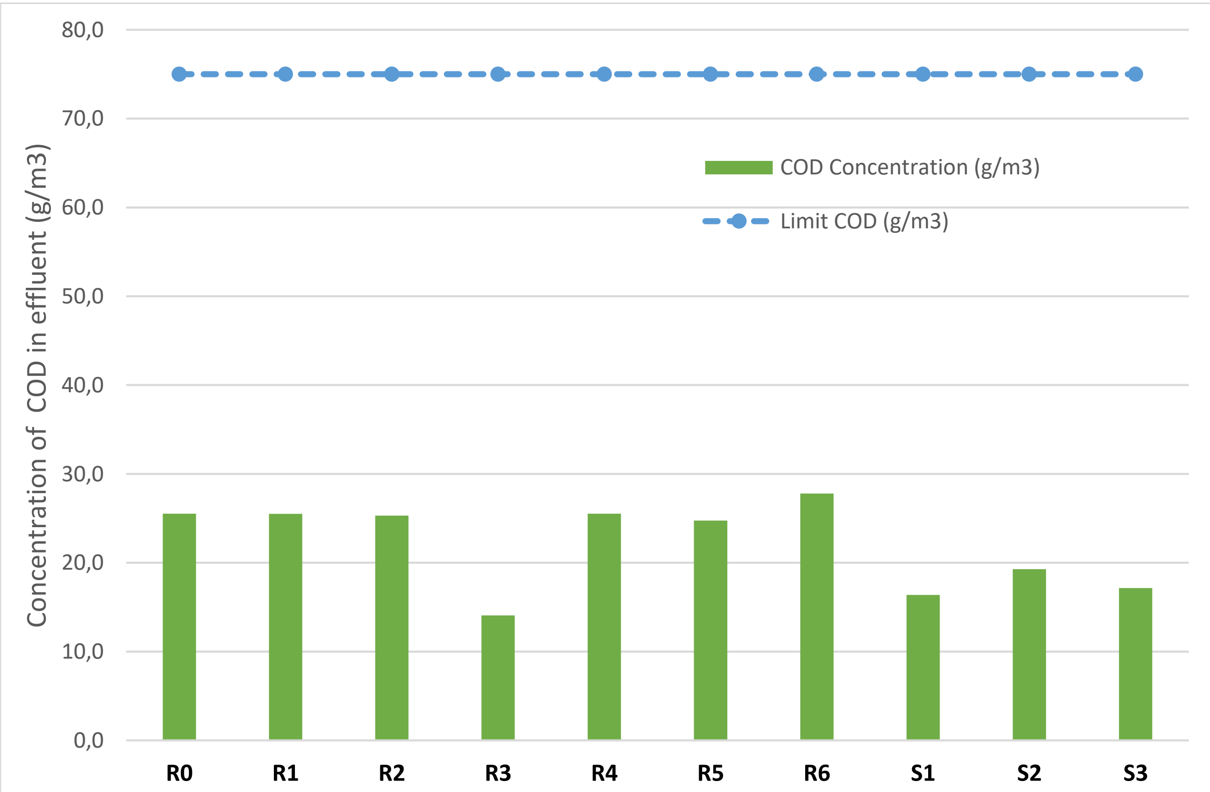


Figure 27: COD concentration to water resources

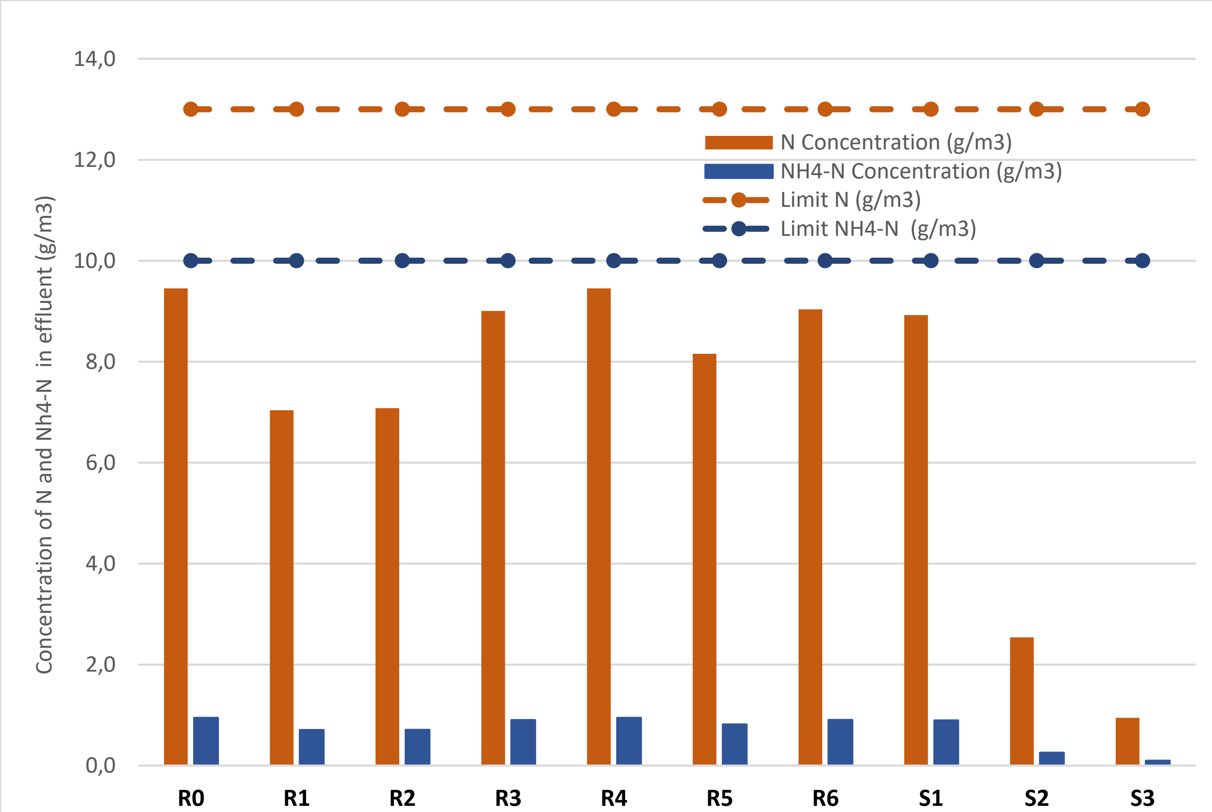


Figure 28: N total and NH_4-N concentration to water resources

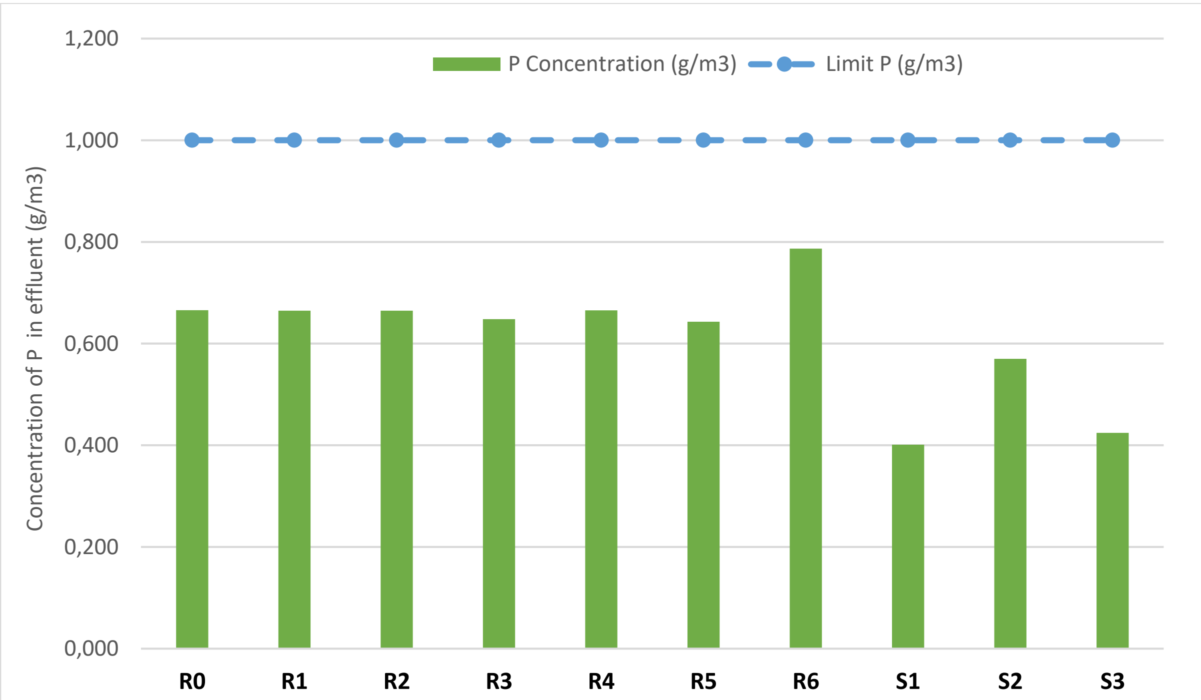


Figure 29: P total concentration to water resources

The comparison of the effluent concentration of nutrient to water resource from different scenarios confirm that the current sanitation system fulfils the legal discharge limits and in source separation concept mainly decreases, which is summarised as follow:

- The COD concentration in effluent of source separation scenario (S1-S3) reduces by 24-36%. Before entering secondary treatment, the separation of organic matter leads to lower effluent concentrations. It also shows that in scenario R3, with the enhancement of primary sludge, by increasing the extraction of primary sludge, the concentration of COD decreases significantly by 45% compared to the reference scenario.
- The lowest N concentration to water resources occurs in source separation scenarios S2 and S3, where urine separation has happened. Urine separation in scenario S2 decreases the effluent of N concentration to 73% compared to the reference scenario. In scenario S3, by separation of all domestic waste flow, the concentration of N in an effluent decrease to 90%.
- All separation scenarios (S1 to S3) lead to the decrease of P concentration to effluent by 14-40% compared to the reference scenario (R0). It occurs due to precipitation of P by separated urine stream and greywater. Scenario R6 with the P recovery from Ash shows the highest P concentration to effluent. It happens because in reference scenario (R0), P concentration is reduced by the P precipitation process, and the return flow (concentrate) to the inlet of wastewater treatment has less P concentration than return flow in scenario R6, where all P concentration is directed to mono-incineration for P recovery from ash.

Overall, it can conclude that a separation system can reduce the emission of nutrients to water resources. However, a detailed investigation of the different chemical forms of nutrients, e.g., dissolved P compared to P total, is required.

5.2.2 Emission to air: CO_2, CH_4, N_2O, NH_3, and SO_2

CO_2, CH_4, and N_2O are contributors to greenhouse gases and NH_3, and SO_2 indicate acidification potential, therefore in this section, the variation of each gas is analysed for all scenarios (Figure 30-33).

CO_2 emission mainly originated from biotreatment, endogenous respiration, and fossil fuel demand for required energy supply and demand for different processes and transport.

The analysis of CO_2 emission contribution shows that source separation scenarios have higher CO_2 emissions than conventional scenarios. Since the CO_2 emission is strongly dependent on the energy demand, scenario S1, with the highest energy demand, has a net CO_2 emission of 22.1 kg/pe.a, which is caused by the increase in energy demand in dewatering processes. In scenarios S2 and S3 with urine and greywater separation, the emission amount decreases 45 and 27%, respectively, due to reduced energy demand.

Scenarios R0- R3 have partially included the process of co-incineration; the emission of CO2 shows a negative net emission value, which means saving CO_2 emission by substituting the fossil fuel (lignite and hard coal in power and cement plant). As the simulation results show, replacing dewatered and dried sludge with fossil fuel decreases the amount of CO2 (Figure 30) compared to source separation scenarios.

Ultimately, CO_2 emission has relation to the total energy demand in scenarios, and the contribution of transport is 3% for conventional and 8% for source separation compared to total CO_2 emission. The benefit of reducing CO_2 emission in conventional scenarios is determined by substituting biogas and replacing recovered thermal energy with fossil fuel and source separation by replacing biogas production and fertiliser production through nutrient recovery processes.

Methane is mainly emitted from the leakage of anaerobic digestion and off-gas of biological treatment. In general, CH_4 emission is in the range of 0.5 kg/(pe.a), and it is constant in most scenarios. In scenarios S1-S3, there is 10-17% increase due to the nutrient recovery process by struvite precipitation (Figure 31).

N_2O emission is mainly originated from an uncompleted denitrification reaction in wastewater treatment, the production and application of fertiliser, and incineration. The Anammox process for nitrogen removal leads to a dramatic increase in N_2O emission in scenarios R1 and R2, where an Anammox process for sludge liquor treatment consider. It contributes 89% of the total N_2O emission of these scenarios. The other main emission source is incineration, which is in 43% of total N_2O emission in scenario R4 and decreases to 25% in source-separated scenario S3. However, the amount of emitted gas is less than 0.4 kg/(pe.a), but due to the strong effect of N_2O in greenhouse gases, it is necessary to consider (Figure 32).

NH_3 emission is emitted from the leakage of biogas production through anaerobic digestion and biological treatment. It mainly arises in source separation scenarios regarding the application of recovered nutrients from separated urine. However, the substitution of organic fertiliser with mineral fertiliser saved the emission caused by mineral fertiliser production as a credit (Figure 33).

Scenario R6 with P recovery from ash shows the lowest net value. It indicates the substitution of recovered nutrients with NH_3 emitted from other processes by optimising the conventional concept for nutrient recovery. Although source-separated scenarios have the same range of net NH_3 emission as scenario R6, there is more emission due to the application of liquid fertiliser produced in the source-separated concept.

Overall, CO_2 has a significant contribution compared to each gas in total emission to air compared to CH_4, N_2O, and NH_3. Since each of these gases has different effects on Global Warming Potential, acidification, and eutrophication, this potential for each scenario is observed in the next section.

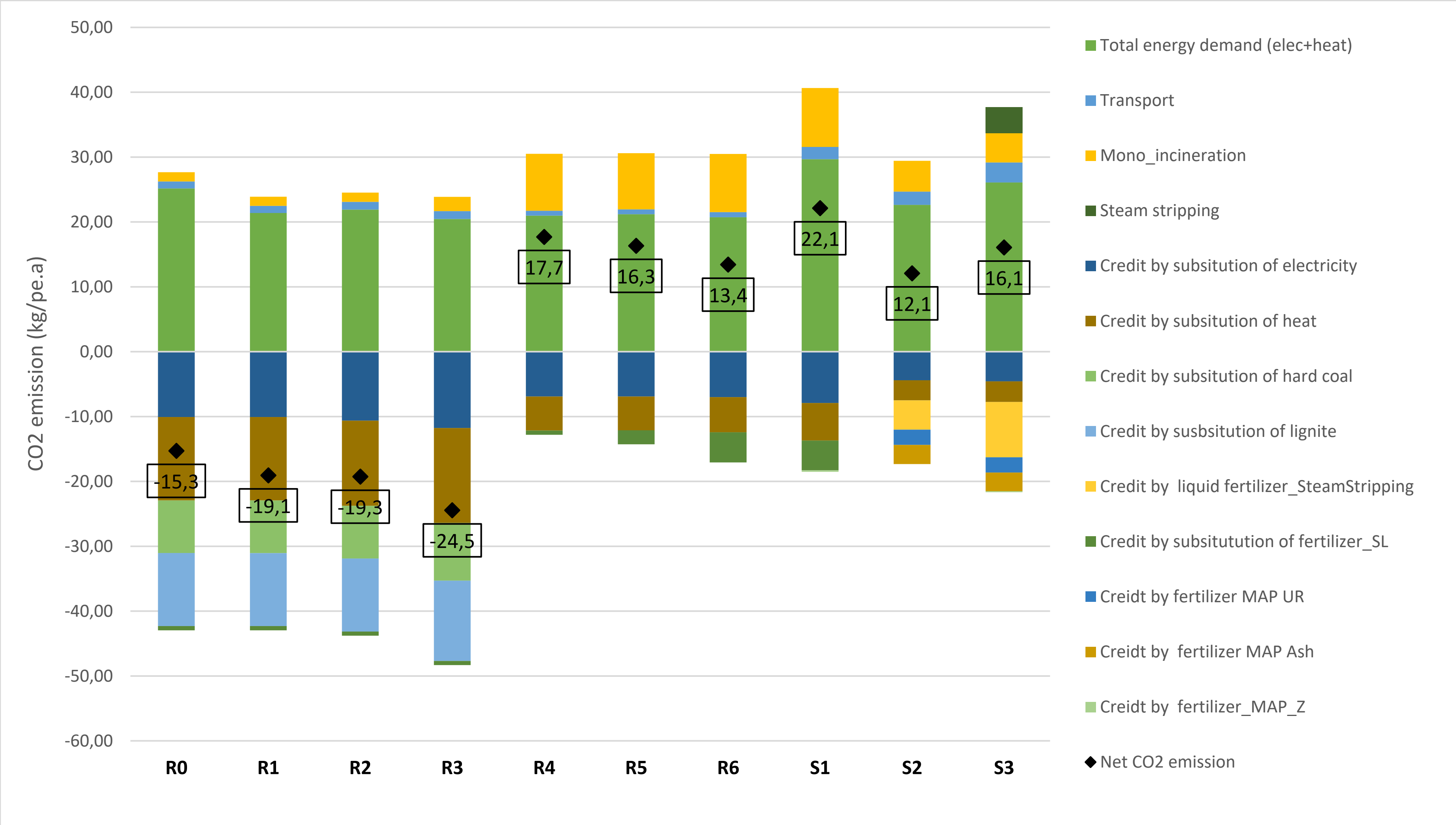


Figure 30: CO_2 emission

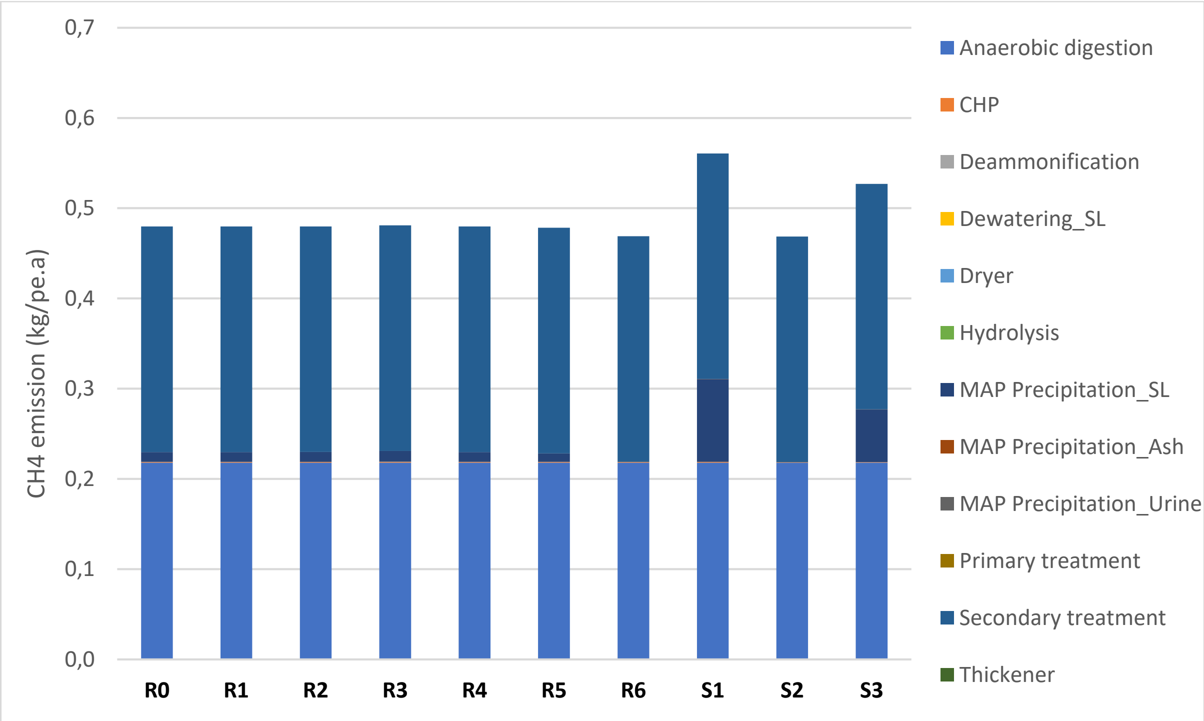


Figure 31: CH_4 emission

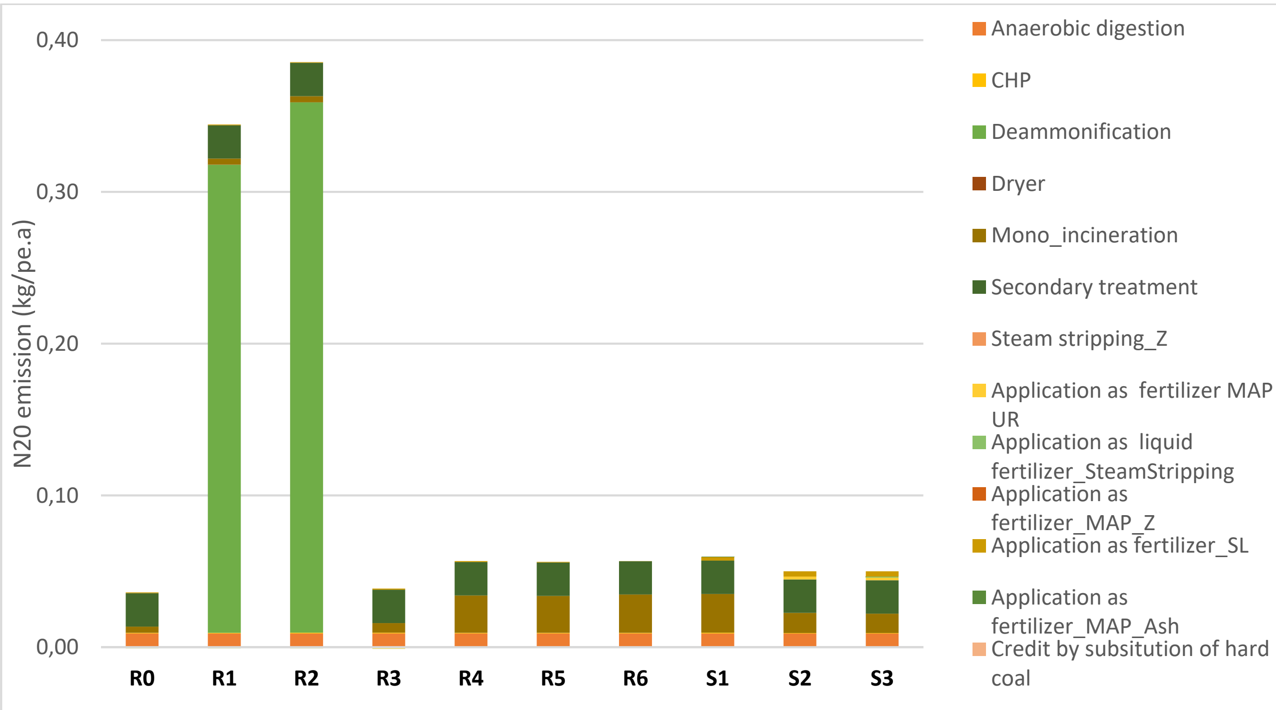


Figure 32: N_2O emission

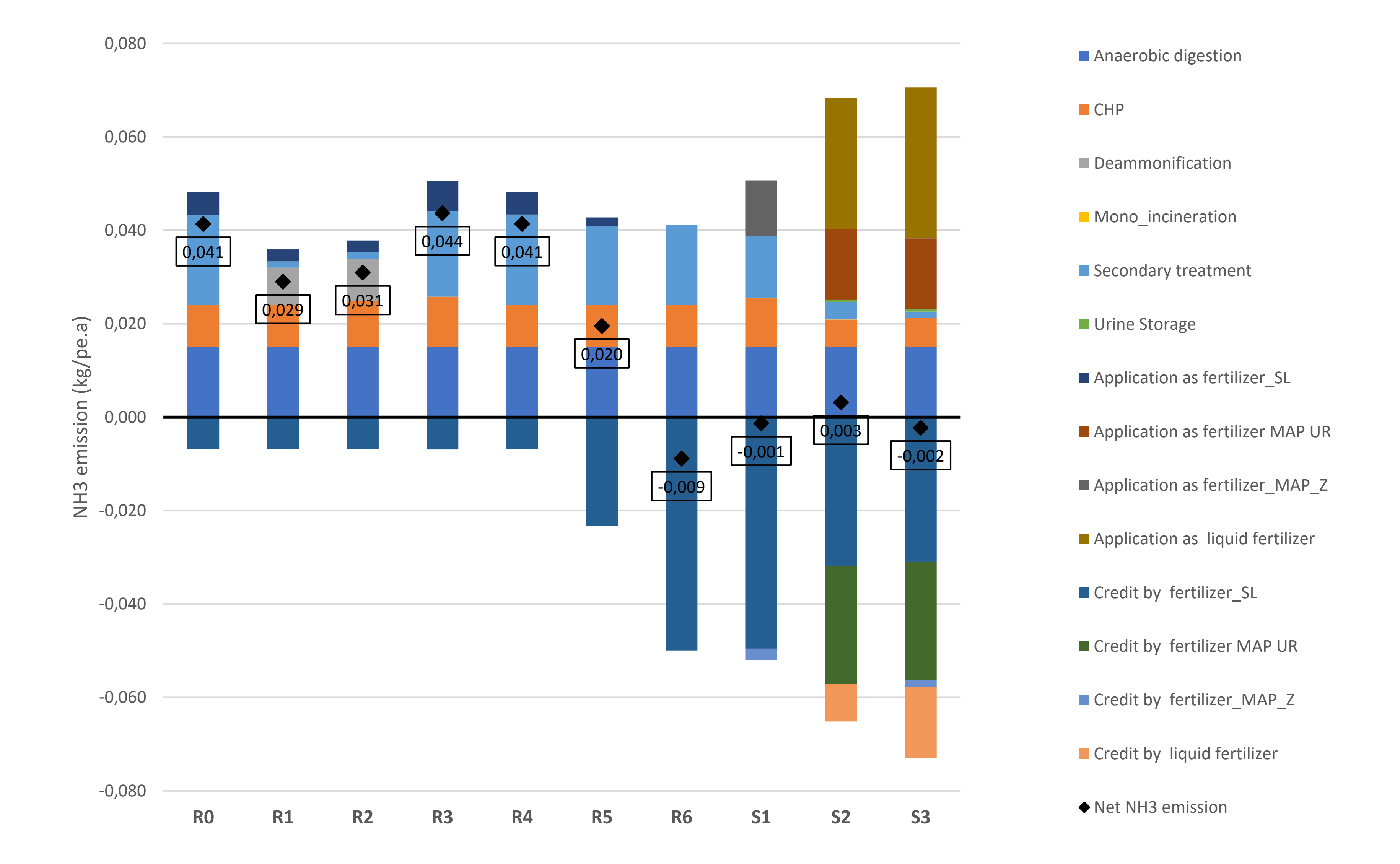


Figure 33: NH_3 emission

5.2.3 Global warming potential

Global warming potential indicator is strongly related to the fossil energy demand due to CO_2 emission from non-renewable fossil fuels. In addition, the emission of N_2O and CH_4 also has a strong effect on global warming. The global warming potential of the different scenarios shows a wide variation of net GWP, between -14.98 and 44.87 (kg CO_2-eq/(pe.a)) (Figure 34).

Scenario R1 and R2, with respectively 35.20 and 44.87 kg CO_2-eq/(pe.a), show the highest effect on global warming potential, and it has a 450% increase compared to the reference scenario. It occurs due to the high emission of N_2O during side-stream treatment with Anammox, which shows that although the Anammox process can save energy of the biological process, the high emissions of N_2O can balance this benefit by generating more greenhouse gases.

Scenario R3, by applying co-incineration, shows the most reduction of greenhouse gas emission with a net value of -14.98 kg CO2-eq/(pe.a), originating from the substitute of lignite and coal with dried sludge in a co-incineration plant.

The net GWP of the source separation scenario reduces compared to most conventional scenarios. Net value in these scenarios originated from the saving of greenhouse gas emissions to produce mineral fertiliser and the substitution of energy obtained from biogas production.

In general, the GWP indicator is strongly related to the energy demand. The comparison of GWP with the cumulative energy demand of different scenarios shows the same pattern of variation (Figure 26). However, the emission of N_2O has a strong influence on GWP. Although source separation scenarios S1-S3 show high GWP with 68-110% higher than the reference scenario, the fertiliser substitution decreases the negative effect of this higher emission.

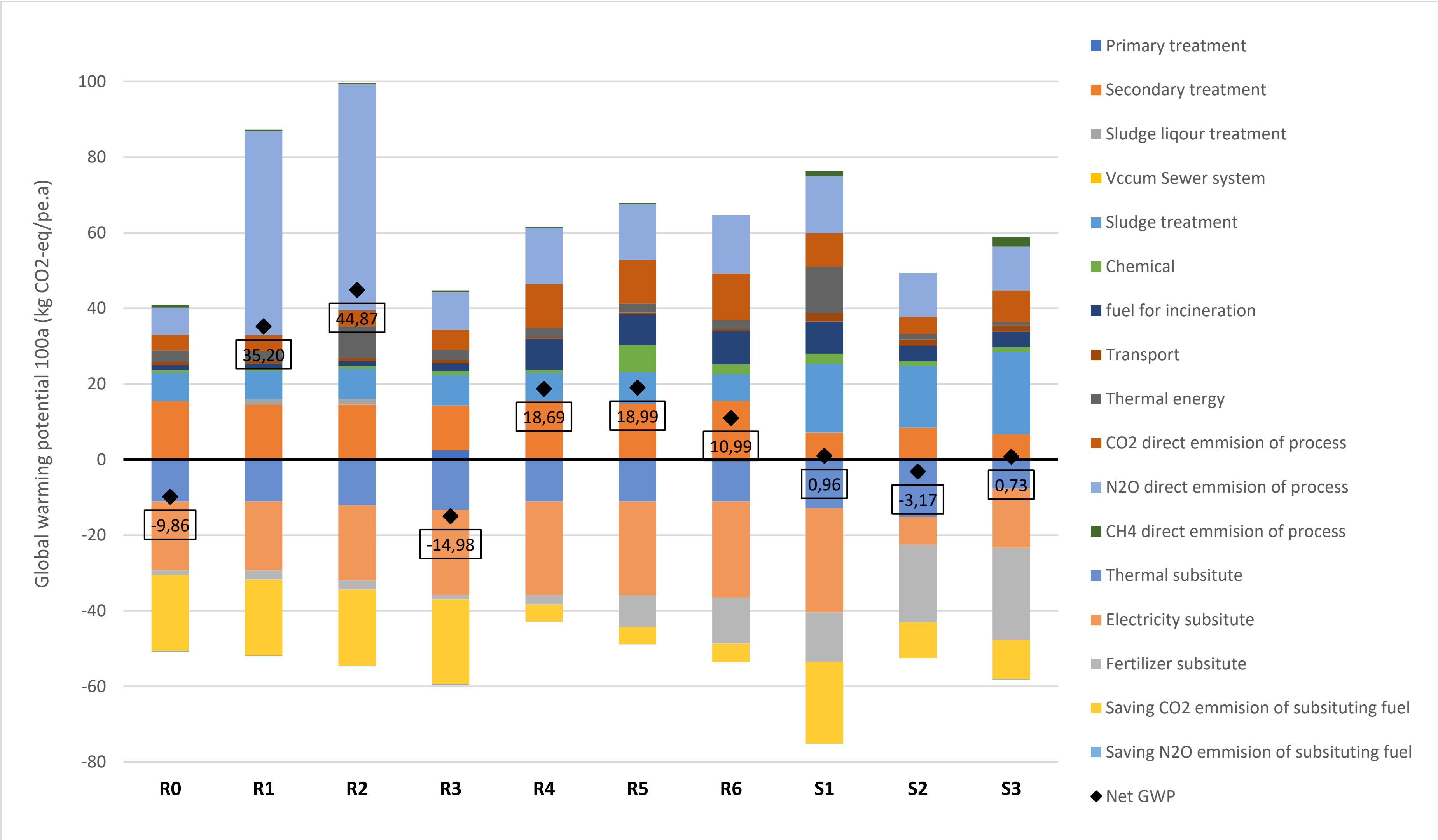


Figure 34: Global warming potential of defined scenarios

5.2.4 Acidification potential

The acidification potential of different scenarios is presented based on the SO_2-eq in Figure 35. According to the net value of acidification potential reference scenario, R0 to R9 has the highest value of 0.032 kg SO_2-eq/(pe.a), and the lowest occurs in scenario R6 by P recovery from ash.

Reference scenario R0 shows higher acidification potential than the other scenarios due to nitrogen elimination in the side-stream and decreasing the emission of NH_3 from the wastewater treatment process. The lower value of net acidification potential in scenario R6 is due to substituting mineral fertiliser with the recovered P from sludge liquor and ash.

Source separation scenarios S1 to S3 indicate the higher net acidification potential value compared to scenario R6 with the range of 36-110%. However, the direct emission of NH_3 is relatively high due to the direct emission of organic fertiliser originating from urine application.

As it is shown in Figure 46, the emission of NH_3 is considerably high in scenarios S2 and S3 originating from the emission by application in agriculture; however, it is offset by the saving of SO_2 emission, which releases to air by the production of mineral fertiliser. However, these scenarios show negative net values and close to zero, caused by saving of SO_2, $NH_{3,}$ and NO_x emission from mineral fertiliser production.

In general, the operation of different processes in all scenarios indicated the increase of acidification potential. However, on the other side, the optimisation processes in each scenario can offset this amount.

5.2.5 Eutrophication potential

The main source of eutrophication is related to phosphorus, nitrogen, and organic matter emissions to water resources. The elimination of P from effluent and recovery from sludge/ash and substitution of P mineral fertiliser with recovered P cause a substantial reduction of the phosphorus release into surface water can improve eutrophication potential in water resources. In addition, the atmospheric decomposition of nitrogen gases (e.g., NH3) affects this impact category (Remy, 2010). Hence, the wastewater treatment process and the associated emission and effluent are decisive for comparing different scenarios.

Reference scenario R0 shows the highest net eutrophication value (0.11 kg P-eq/(pe.a)) and the lowest net value shows in scenario S3 by -1,8 kg P-eq/(pe.a). Scenario R0 represents the conventional wastewater treatment with P precipitation by Airprex to avoid uncontrolled clogging in the sludge line. Scenario S3 represents source separated sanitation concept where P recovery occurs from separated urine and ash with high efficiency (Figure 36).

In source-separated scenarios (S1 to S3), the efficiency of P-recovery is primarily due to the high concentrated wastewater flow and direct precipitation from urine. The major credit originated from the substitution of mineral fertilisers with P fertilisers from treatment processes. In total, all scenarios can decrease EP_{fresh} between 0.1 to -1.8 P-eq/(pe.a).

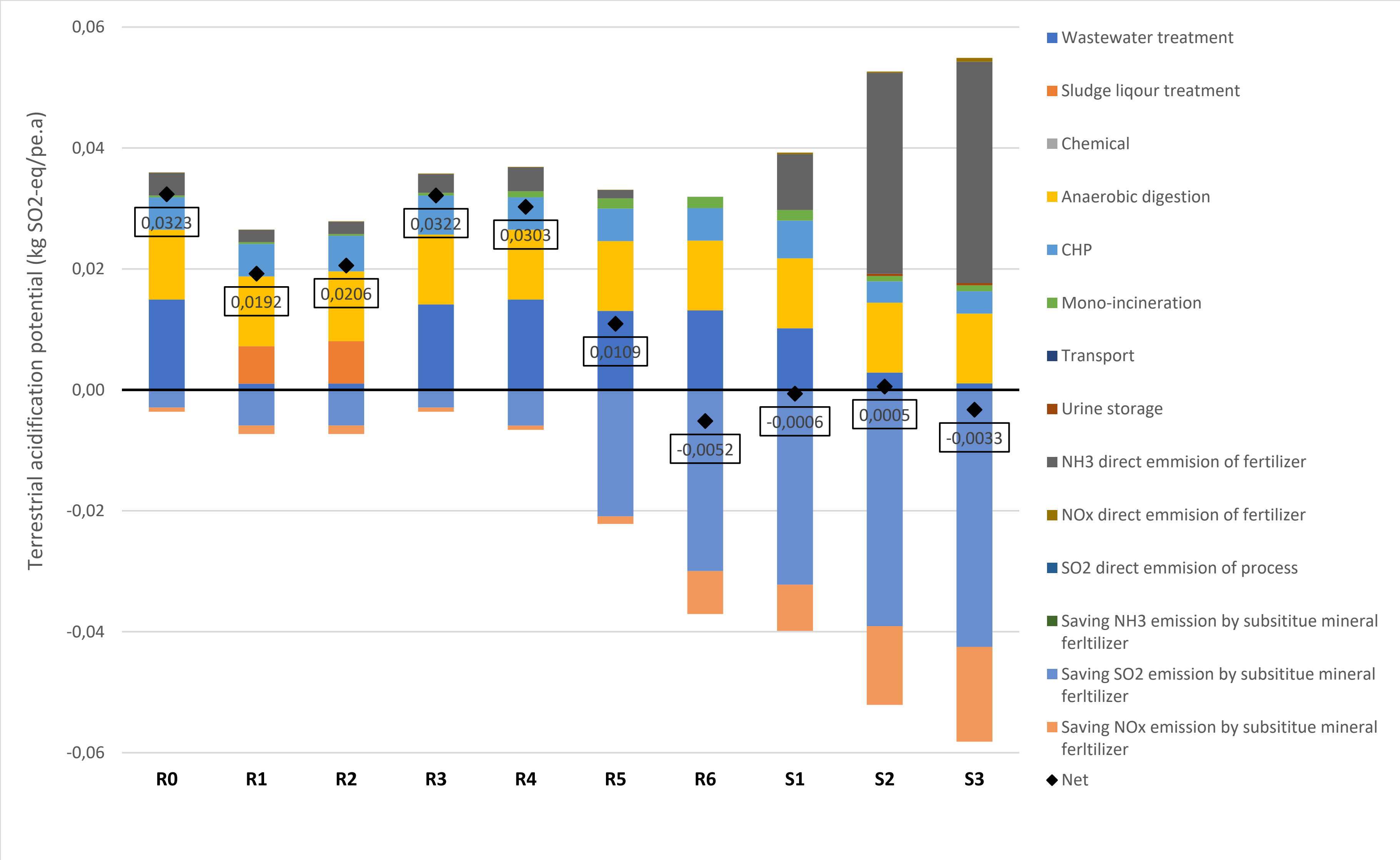


Figure 35: Terrestrial acidification potential of defined scenarios

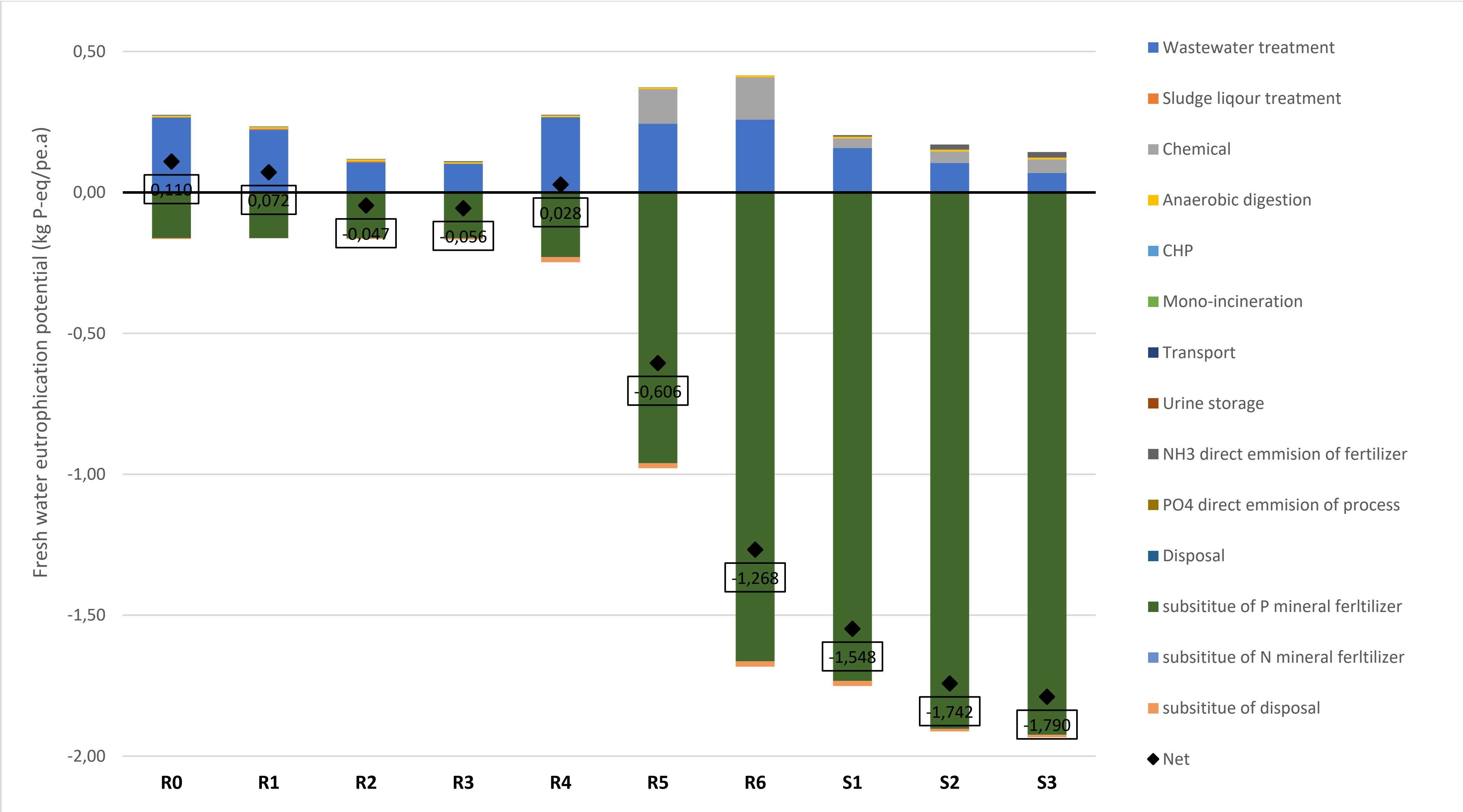


Figure 36: Freshwater eutrophication potential of defined scenarios

5.2.6 Nutrient recovery

The potential of nutrient recovery from different scenarios is shown in Figure 37. The highest nutrient recovery is in scenario S3, where nutrient recovery is carried out in a separated urine stream, and ash originated from disposed sludge of blackwater and greywater. Based on the percentage of recovered nutrients (Table 44), 82.4% of phosphorus could be recovered in source-separated scenario S3.

Nutrient recovery in the reference scenario and scenarios R1 to R4 is the same amount due to the focus of these scenarios on energy efficiency and implementation of the same processes for struvite precipitation. The struvite harvesting in these scenarios is mainly for operation improvement to avoid the uncontrolled P, and it can be considered as a maintenance solution. These scenarios led to less polymer consumption by up to 15-25% and increased sludge dewaterability for disposal up to 4% (Remy 2015, Kraus et al. 2019). However, the obtained product could be used as a fertiliser, e.g., Berliner Pflanze.

The amount of nutrient recovery is increased from scenario R5 with the P recovery process from sewage sludge with acid leaching, and the percentage of recovered P is up to 33%. R6 has the highest P recovery for conventional sanitation systems by acid leaching in ash with a recovery rate of 72% based on the defined efficiency rate in the model.

Source separation scenarios show higher nutrient recovery potential compared to the conventional scenario. Due to the reduction of nutrient losses in source separation and a high concentrate of material, the efficiency rate can reach 82%.

It should be considered that the presented results are highly dependent on the assumption of the efficiency of the processes, which may change based on different conditions. However, source separation results are primarily based on assumptions and upscaling of literature reviews. The results of this study based on the developed model are compatible. According to the results of other studies, the potential of P recovery from conventional concept for sewage sludge lies in the range of up to 70% and for sewage sludge ash up to 90% based on the phosphorus contained in the wastewater treatment (Montag et al. 2015, Kraus 2019).

Table 44: Ratio of recovered nutrient from different scenarios

Parameter	Unit	R0	R1	R2	R3	R4	R5	R6	S1	S2	S3
P recovered	kg/pe.a	0.07	0.07	0.07	0.07	0.07	0.24	0.53	0.56	0.60	0.60
N recovered	kg /pe.a	0.04	0.04	0.04	0.04	0.04	0.12	0.26	0.28	0.30	0.30
Sum	kg /pe.a	0.11	0.11	0.11	0.11	0.11	0.36	0.79	0.84	0.89	0.90
P-input	kg /pe.a	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73	0.73
Potential of recovery	%	9.85	9.84	9.84	9.86	9.86	33.19	71.94	76.50	81.71	82.38

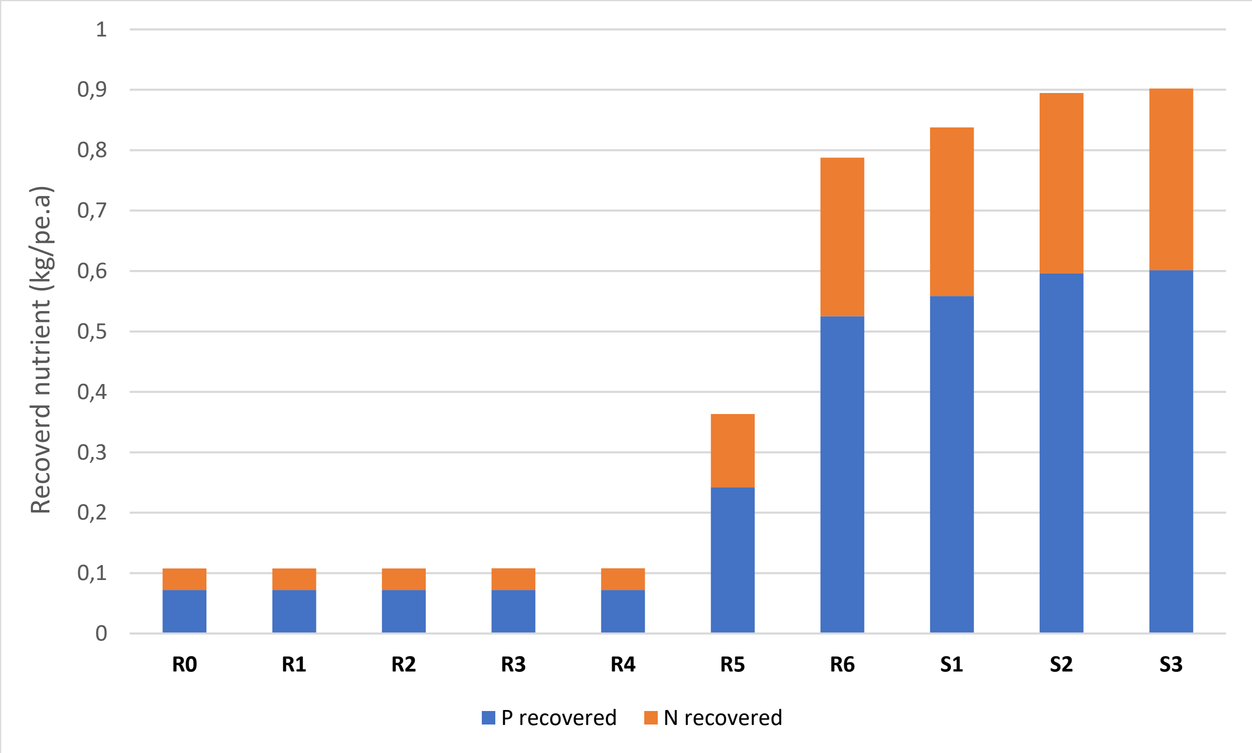


Figure 37: Recovered nutrient from different scenarios

5.3 Analysis of economic aspect of scenarios

The developed tool estimates the total investment and operation costs of different scenarios. The presented results give an overview of investment and operation costs.

Investment cost in Figure 38 shows that source separation scenarios have higher investment costs compared to conventional scenarios. Scenario S3, with separation of urine and greywater, has 45% increase in investment cost. In-house installation, including vacuum toilet, urine diversion toilet, and separated piping line for each flow, are the main contributors to these scenarios' increase. Three flow pipe system requires 2.4 and two flow system requires 1.75 times more pipe systems is needed compared to conventional system (Oldenburg, 2007). These factors significantly influence the investment cost, and it is represented in the results.

In conventional scenarios (R1 to R6) where there is an optimisation in processes, there is up to 5% variation in total investment cost compared to reference scenarios. The sewer system is the core investment cost with 70% contribution in each scenario. In a conventional system, around 75-85% of the cost are fixed costs independent of the amount of wastewater, 14% Personnel cost, and 10% operation cost. Thus, treatment and disposal of sewage sludge only account for 4%, which means that changes in disposal have only a minor impact on the overall costs and make only a minor contribution to increasing the wastewater costs (Roskosch und Heidecke 2018).

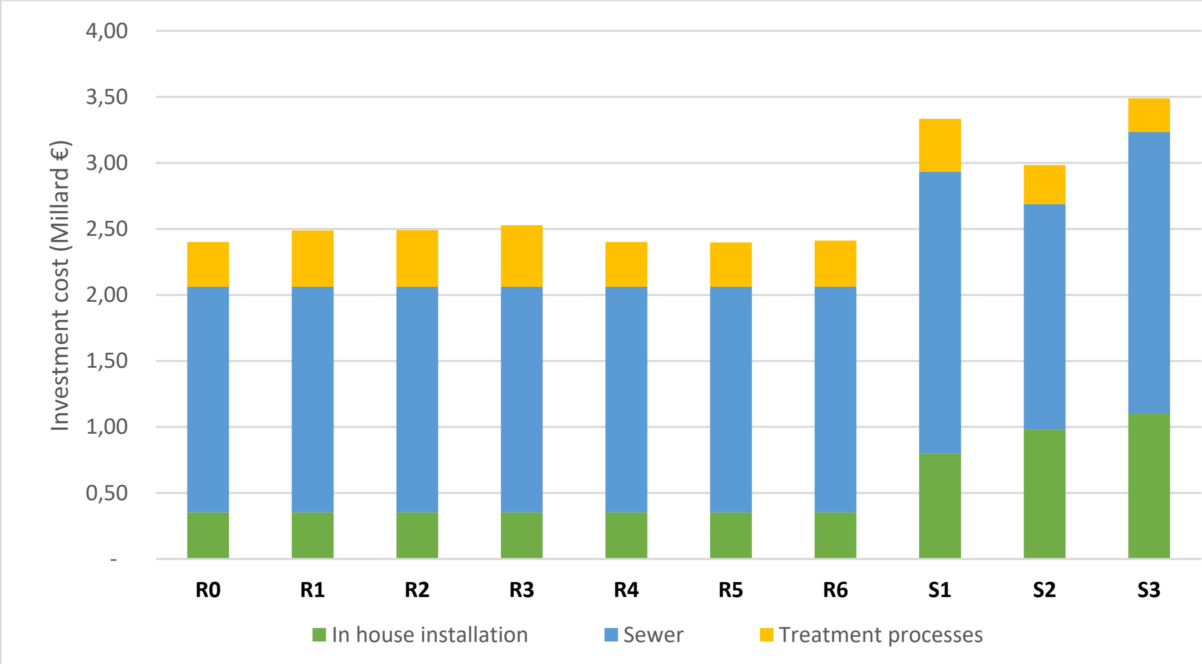


Figure 38: Investment cost of all scenarios

Source separation technologies have shown that the operation cost of this system is less due to the distribution of flow to small units in source separation (Figure 39), the staff capacity might not fully used. Increasing automation can help decrease these costs and, on the other side, will increase the capital cost, affecting the feasibility of these processes. Oldenburg et al. (2007) stated operation cost of source separation is lower than the conventional system, whereas total project costs are comparable or higher.

Dockhorn made a detailed cost analysis for GK5 urban sanitation and identified benefits derived from the source separation system (Dockhorn 2007a). These benefits originate from cost reduction by treating less polluted wastewater and generating biogas and organic fertiliser production.

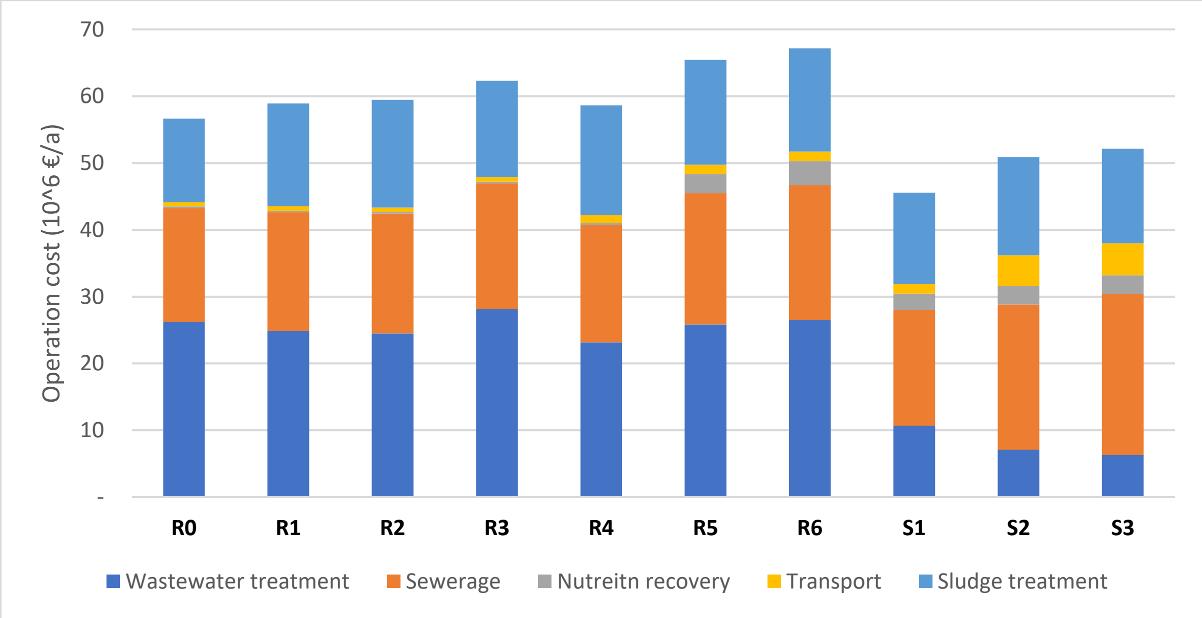


Figure 39: Operation cost of all scenarios

The benefit of each scenario is calculated based on the revenue from each scenario (Figure 40). The revenue from Source separated scenario S3 is the highest, and it leads to 30% of replacement of operation cost. It originated from the recovered nutrient (N and P), saving drinking water and energy in this scenario. However, this benefit calculation is highly dependent on the value that the market is defined for the recovered products.

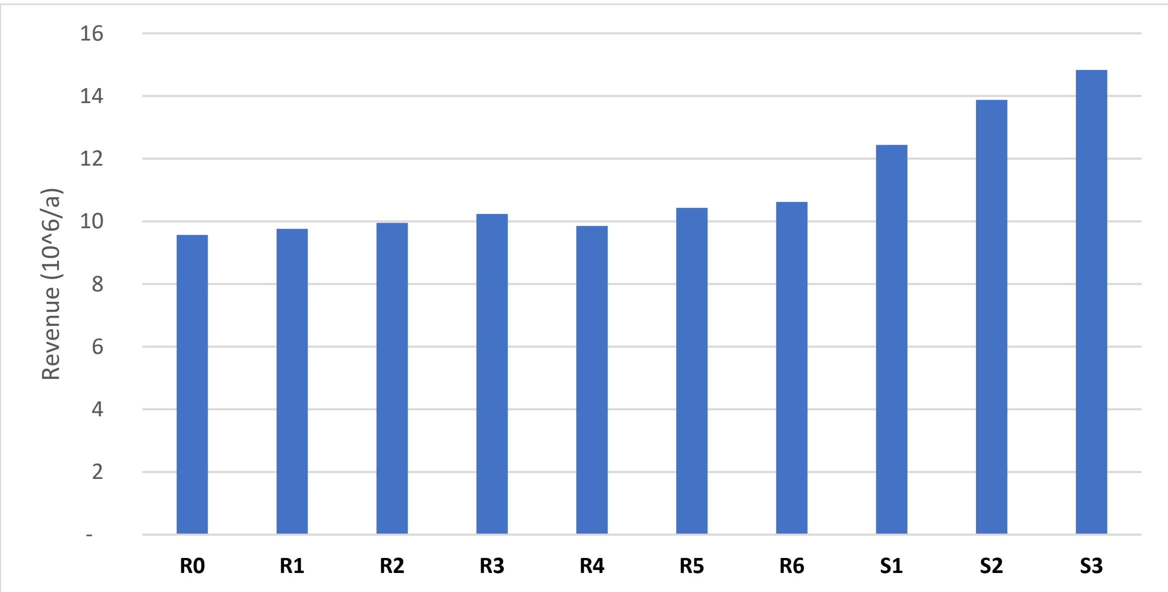


Figure 40: Revenue of all scenarios

5.4 Analysis of social aspect of the scenarios

The social aspect plays a vital role in the sustainability assessment of the sanitation system. Specifically, the successful implementation of source separation is highly related to the social aspect of end-users. The social indicators are qualitative, and in this study, the comfortability, affordability, and health/ hygiene of each scenario are investigated.

Assessing these indicators in the investigated scenarios shows scenario R0-R6, where conventional sanitation is implemented. There are higher scores for health and hygiene to concept due to long term of application.

In principle, separation scenarios reveal the crucial impact of social aspects regarding the direct impact on the user's daily life. In a separation scenario, social perception and acceptance must be ensured.

Changing the comfortability of users and habits plays an essential role in accepting such a significant transformation from conventional to the new sanitation system.

Public acceptance of novel facilities like vacuum toilets meets the user's comfort zone, and it highly depends on the proper function of this novel method and affordability.

According to the survey done in the Sneek project where blackwater and greywater were collected separately, most inhabitants evaluate the source separation system as practical and hygienic and express their satisfaction to participate in Eco-friendly practices (Lema und Suárez 2017). However, some practical aspects, such as the noise from the vacuum toilet, require further consideration to make it more user-friendly. The same results were found in Berlin's SCST project (SCST, 2007). In the study of Lienert und Larsen (2006), most users affirmed that the design, hygiene, and smell in urine separation toilets are equal to the conventional toilets. However, accepting these early-stage technologies was challenging due to problems with maintenance, such as blockages and toilet paper disposal.

However, awareness and education of the general public play an important role in accepting the novel recovery process and its product. Increasing the user's knowledge about different aspects of sustainability, i.e., the effect of greenhouse gases, the usage of detergent, and the side effect of fertiliser application in water resources, plays an important role that is not easy to measure on a quantitative scale.

In addition, farmers as an essential target group who are the user of the by-product of wastewater treatment and application of fertiliser in the land should be considered precisely. They will, understandably, not be willing to consider any option that will require significant changes in practice without increased profit or, even worse, decrease crop yields or profit. An unintended consequence would appear if fertiliser generated from urine and blackwater were less effective, or fertiliser quality and availability are not reliable or have a social stigma. Pricing, financing has the primary influence on the behaviour of farmers.

Overall, social indicators are qualitative and complex to measure objectively, and often their meaning and relevance are suggested by local stakeholders (Cossio et al. 2020a). The social dimension and associated indicators are considered key to the sustainability assessment of sanitation concepts, although standard indicators are still developed(Palme et al., 2005; Popovic und Kraslawski 2018).

5.5 Sustainability assessment of all scenarios

The overall results obtained from different aspects of sustainability assessment of investigated scenarios demonstrate in Figure 41. Source separation sanitation concept (scenario S1-S3) shows an improvement in terms of ecological aspect compared to conventional scenarios (R0-R6). By contrast, the social aspect shows a decrease of score in source separation compared to conventional sanitation. Economic and technical aspects show the same flocculation in both concepts.

Figure 42 shows that the reference scenario has the highest score (3.07) due to the high impact of social indicators. Scenario S1, with greywater separation with (3.03), has the highest score for the source separation concept.

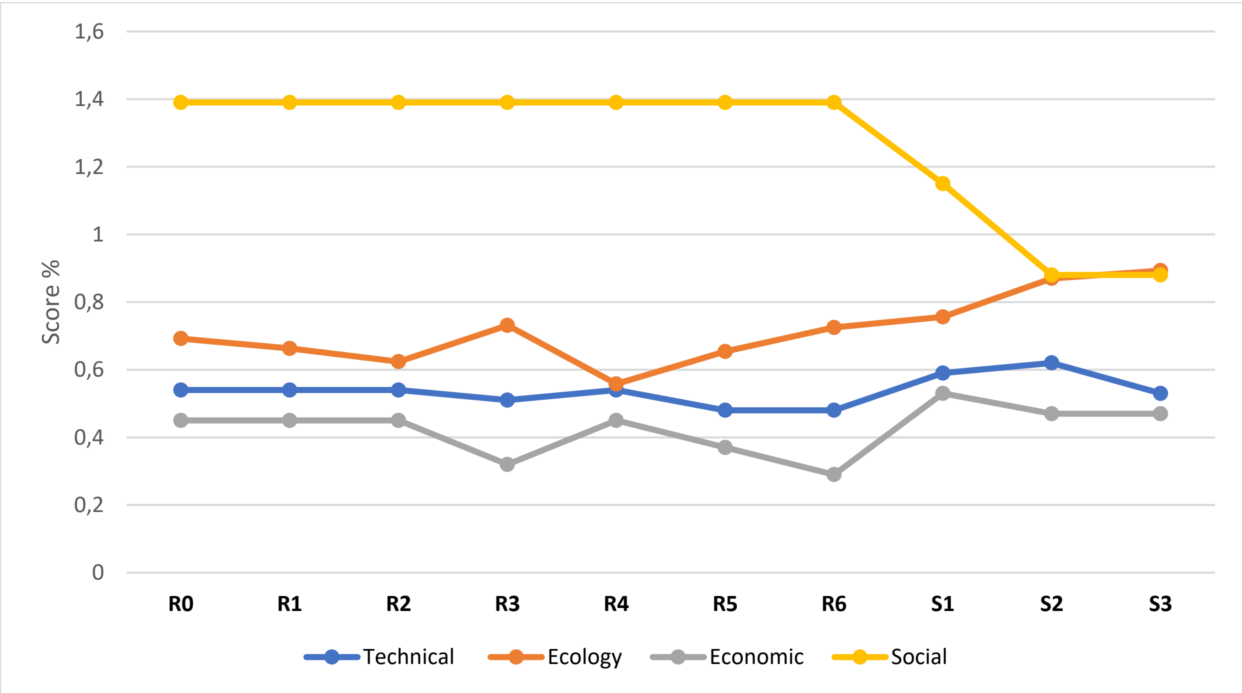


Figure 41: Assessment of sustainability aspects of investigated scenarios

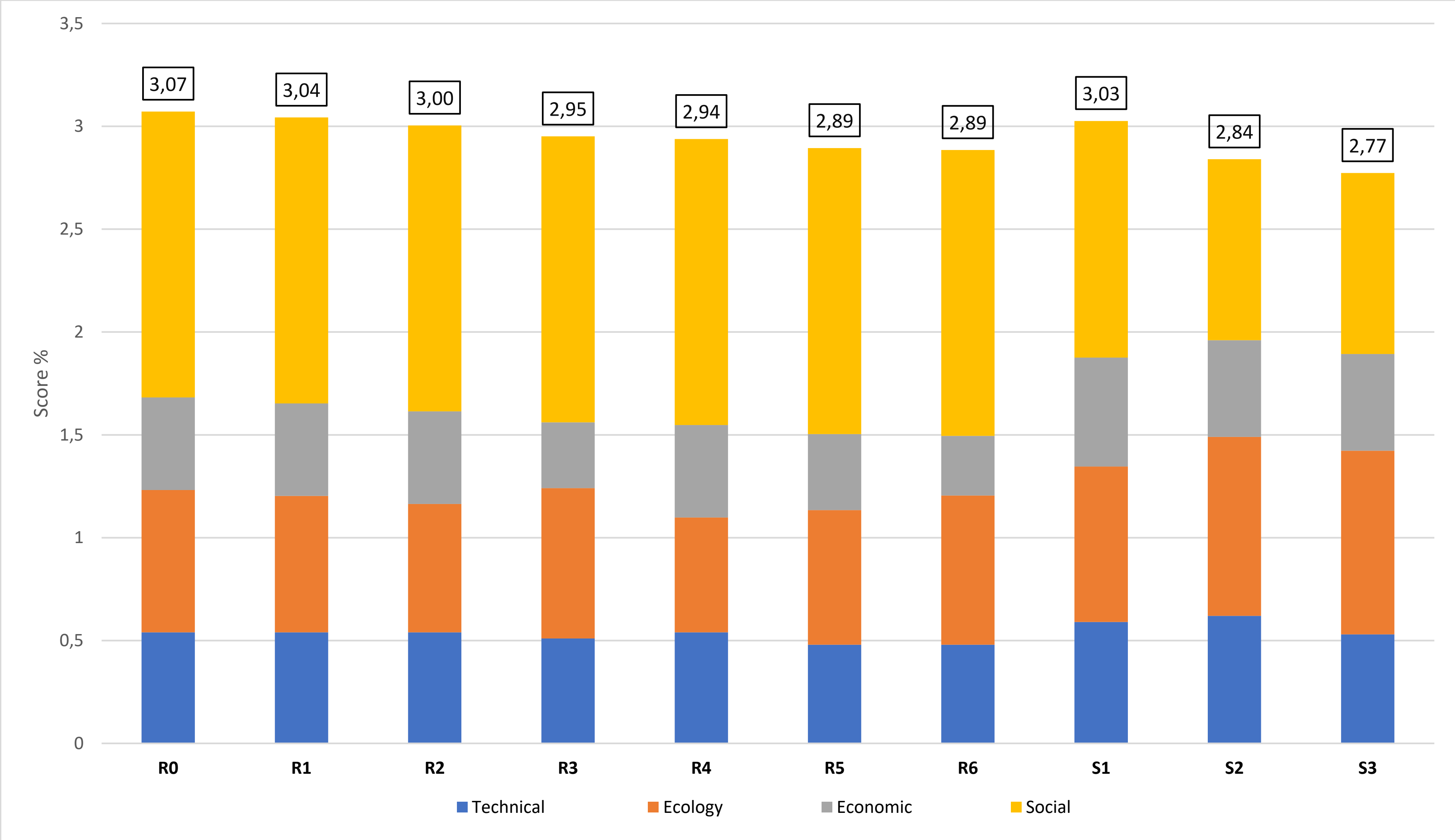


Figure 42: Sustainability assessment of investigated scenarios

6 Summary and conclusion

In this study, a material flow analysis tool for urban sanitation concept was developed to choose a more sustainable concept in terms of ecological, economic, technical, and social.

This study contains two main steps. First, a decision-making support tool is developed to assess material flow analysis in terms of sustainability criteria. Second, a comparative scenario-based assessment of conventional and source-separated concepts was carried out.

The study indicates that the MFR3 method can provide a practical tool for assessing the resource recovery efficiency from different sanitation concepts. A range of different scenarios is assessed in terms of sustainability indicators. Although none of the concepts is the premiere for all indicators, the results present a clear basis for decision-making by pointing out which part can be optimised to reach the design goal.

The findings are following:

- This study successfully presented the comparison of conventional and source separation concepts. The result is a visualization of material flow to have an overview of the whole system and, in addition, by presenting a detailed result for each process. A different aspect of energy demand, material demand, resource recovery, and cost could be analysed.
- The developed tool in this study is identified for addressing the complex process of material flow in wastewater flows to provide a comprehensive solution for comparing different aspects of sustainability for different scenarios.
- The use of equations for material flow and energy proved to be effective in this study that is successfully resulted in a suitable material flow analysis to represent a flow condition in each scenario.
- In the present work, conventional and source separation sanitation concepts are evaluated in order to identify the separate collection, treatment, and recovery potential of different wastewater fractions.
- As the results of net energy show, the selection of strategy to apply the generated energy plays an essential role in the outcomes. For example, application of district heat network and transfer the generated heat from incineration for inhabitant's heat systems. On the other concept, to locate the sludge dryer close to the incineration plant, which can increase the heating value of sludge to produce more energy, and consequently, the generated heat energy can be used for the required energy of the drying process.
- Increasing sustainability criteria of urban wastewater systems are obtained by new approaches, which can be a source separation concept for new urban areas or partially source-separated concept, e.g., greywater treatment as a gradual step towards source separation. Moreover, if the source separation concept cannot be implemented, the current sanitation system can be further optimised.
- The results of this study show that optimisation of existing systems can also lead to a proper outcome in terms of sustainability.

- The results of the scenarios for optimisation of conventional and source separation concepts show the variation of selected sustainability indicators.
- The presentation of material flow Sankey diagram provides the possibility to monitor the mass flow and the main element in wastewater treatment, including COD, N, P, DM, and oDM.
- Energy flow and calculation of related main sustainability criteria
- Since process units are defined based on independent equations for each material flow analysis, the defined unit process can be used for both conventional and source separation concepts where load and concentration of flow can be identified by the tool.
- The synergistic combination of the two methodologies decision making support system, and LCA is implemented to address the design and assessment of treatment facilities. It leads to identifying the most sustainable options, embracing a wide variety of analysis criteria simultaneously, and enhancing the calculation of environmental savings.

There is a long way to present a tool to make decisions for a more sustainable alternative for the sanitation system. However, the results of the developed tool in this study can support decision-making processes. The tool helps to give a general overview of the material flow and energy and provides an assessment for evaluating emissions, energy demands, and related environmental issues like eutrophication and acidification.

The main difficulty is related to the uncertainties of the elementary data, which consequently leads to assumptions. Technical assumptions can be verified by referring to literature values. However, verification of cost data and economic impact is a complex process, and values are related to various factors, e.g., local decision policy, price fluctuation of material, etc.

Although the cost analysis was developed to calculate the cost-benefit of the selected scenarios, the cost analysis requires more detailed studies to cover different types of cost data and identify the relation of these data with the economic behaviour of the product in the market.

The social aspect plays a vital role in sustainability assessment results; however, the qualitative characteristic of the indicator is highly related to the assigning related scores. Although these scores are defined based on considering different social studies, they can be changed based on different interpretations, leading to a change of final assessment results.

6.1 Outlook for future research

Several open issues are identified and could be addressed in future research in order to enhance the applicability of the model to real-life conditions:

- Further validation is needed to test the complex integration of material
- Further different forms of nutrients can extend. Since the material flow is done only based on total N and P, it could be more accurate results when a different form of P, especially for dissolved P, is considered

- There is still potential for extension of temperature dependency, especially for anaerobic digestion processes and the investigation of hydrolysis
- Regarding COD, biogenic carbon source, the model can be extended to account for biogenic and non-biogenic carbon proportion for anaerobic digestion
- More study about the emission from the different processes may lead to accurate results. Since the model can calculate the emission and the greenhouse gas factor on global warming but the existence of the related data bounds it
- Material flow analysis for different materials and different processes from the source to disposal for a different aspect of sustainability leads to extensive results for different aspects, which may not be required for each decision support process. Extracting essential parameters from the model and following them in the output section could be an approach to consider the simplicity of this tool
- Although the primary goal of the model was to provide a simple model which could be easily used as a decision-making support tool for urban sanitation concept, however, due to disaggregation of the processes and considering various materials which play an important role in analysis, the final tool sounds to be complicated. As a final product, the developed model is a complex model which considers most of the main parameters in material flow analysis. Simultaneously, it could be used as a simple tool by considering one specific material (e.g., N) and following that in the different processes. Since the defined material is independent, it would be easy to use them without influence on the other material flow. Only each material load is dependent on the mass flow, so it should be considered.
- Micropollutants and heavy metals are getting important in wastewater treatment processes. The flow analysis of these materials could lead to exciting results, especially for applying recovered nutrients. The currently developed tool has a high potential for integrating new materials flow. It can be done quickly by setting a new material flow in the model. The challenge would be the availability of accurate input data for different processes and mass balance of them in each section.
- Hence, an intensive economic study is required to develop an economic model which can cover most of these factors and represent the actual situation.
- The presented model can be understood as an appropriate point for the further design of a software-based simulation model for the source-separated sanitation concept. It needs improvement and a more detailed development to extend the model for other innovative processes (e.g., heat recovery from greywater, carbonisation, using the sensor for source separation of flow).
- Enhancement of the further input parameters like heavy metals, micropollutants different form organic and inorganic carbon and different forms of N and P. Main nutrients (COD, N, P) are identified in this study due to lack of data for defining mass balance of the mentioned parameters for each process unit. Definitely, in the case of existing data, simulation of material flow based on them can provide more accurate outputs.

- Developing the related equations to represent the different forms of material can improve the accuracy of the results. For example, by differentiating degradable and inert COD, there would be the possibility to calculate the variation of biogas production based on carbon input to the digester.
- Develop the process formulation by considering retention time and temperatures.

Annex A

A.1 Scoring of sustainability indicators

A.1.1 Ecological

Table A. 1 Scoring system for ecological indicators

CO_2 emission (kg/pe.a)	Grade	Score
< (-30)	Very high	5
(-10) - (-30)	High	4
(-10) - (10)	Moderate	3
10-30	Low	2
>30	Very low	1

N_2O_direm (kg/pe.a)	Grade	Score
<0.012	Very high	5
0.025-0.05	High	4
0.05-0.075	Moderate	3
0.075-0.1	Low	2
>0.1	Very low	1

CH_4_direm (kg/pe.a)	Grade	Score
<0.15	Very high	5
0.15-0.35	High	4
0.35-0.45	Moderate	3
0.45-0.55	Low	2
>0.55	Very low	1

Net NH_3 emission (kg/pe.a)	Grade	Score
<0.01	Very high	5
0.01-0.03	High	4
0.03-0.05	Moderate	3
0.05-0.07	Low	2
>0.07	Very low	1

Net SO_2 emission (kg/pe.a)	Grade	Score
<0.00005	Very high	5
0.00005-0.0001	High	4
0.0001-0.0004	Moderate	3
0.0004-0.0016	Low	2
>0.0016	Very low	1

COD Concentration (g/m^3)	Grade	Score
<20	Very high	5
20-25	High	4
25-30	Moderate	3
30-35	Low	2
>35	Very low	1

P Concentration (g/m^3)	Grade	Score
<0.4	Very high	5
0.4-0.6	High	4
0.6-0.8	Moderate	3
0.8-1	Low	2
>1	Very low	1

N Concentration (g/m^3)	Grade	Score
<2	Very high	5
2-6	High	4
6-10	Moderate	3
10-14	Low	2
>14	Very low	1

Energy (kWh/pe.a)	Grade	Score
<18	Very high	5
18-24	High	4
24-30	Moderate	3
30-36	Low	2
>36	Very low	1

Water supply lit/ pe.a	Grade	Score
<4000	Very high	5
4000-7000	High	4
7000-10000	Moderate	3
10000-13000	Low	2
>13000	Very low	1

P recovered kg/ pe.a	Grade	Score
>0.4	Very high	5
0.3-0.4	High	4
0.2-0.3	Moderate	3
0.1-0.2	Low	2
<0.1	Very low	1

N recovered kg/ pe.a	Grade	Score
>0.3	Very high	5
0.2-0.3	High	4
0.1-0.2	Moderate	3
0.05-0.1	Low	2
<0.05	Very low	1

Recovered elect (kWh/ pe.a)	Grade	Score
< (-35)	Very high	5
(-25) - (-35)	High	4
(-15) -(-25)	Moderate	3
(-5)- (-15)	Low	2
> (-5)	Very low	1

Recovered heat (kWh/ pe.a)	Grade	Score
< (-60)	Very high	5
(-45)- (-60)	High	4
(-30) -(-45)	Moderate	3
(-15) - (-30)	Low	2
> (-15)	Very low	1

Table A. 2 Scoring of ecological indicators for each scenario

Criteria	Indicator	Sub-indicator	Weighting %	R0	R1	R2	R3	R4	R5	R6	S1	S2	S3
Emission to air	Global Warming Potential	CO_2	0.7	4	4	4	4	3	3	2	2	2	2
		N_2O	1.2	4	1	1	4	3	3	3	3	3	3
		CH_4	0.9	2	2	2	2	2	2	2	1	2	2
		NH_3	0.7	3	4	4	3	3	4	5	5	4	5
		SO_2	0.7	3	3	3	3	2	2	2	2	2	2
Emission to water	Eutrophication Potential	COD	3	3	3	3	5	3	4	3	5	5	5
	Acidification Potential	P	0.5	3	3	3	3	3	3	3	4	4	4
	Nutrient load	N (N total, NH_4-N)	0.6	3	3	3	3	3	3	3	3	4	5
Resource demand	Cumulative energy demand	Electricity /thermal	3.9	3	3	2	2	2	2	2	1	3	3
	Material demand	Chemical supply	1.8	3	3	3	4	3	4	5	3	4	4
Resource recovery	Water supply saving		2.5	2	2	2	2	2	2	2	4	5	5
	Recovered N		0.8	1	1	1	1	1	3	4	4	4	5
	Recovered P		2.5	1	1	1	1	1	2	5	5	5	5
	Recovered electricity		3.5	3	3	3	3	2	2	2	2	2	2
	Recovered heat		1.7	4	4	4	4	2	2	2	2	1	1

A.1.2 Economical

Table A. 3 Scoring system for capital cost

Capital cost (10^9 €)	Grade	Score
<1.5	Very high	5
1.5-2	High	4
2-2.5	Moderate	3
2.5-2.8	Low	2
2.8<	Very low	1

Table A. 4 Scoring system for operation cost

Operation cost (10^6/a)	Grade	Score
<50	Very high	5
50-55	High	4
55-60	Moderate	3
60-65	Low	2

65<	Very low	1

Table A. 5 Scoring of economic indicators for each scenario

Indicator	R0	R1	R2	R3	R4	R5	R6	S1	S2	S3
Capital cost (10^9 €)	3	3	3	2	3	3	3	1	1	1
Operation cost (10^6/a)	3	3	3	2	3	2	1	5	4	4

A.1.3 Technical

Table A. 6 Scoring system for risk of failure indicator and maintenance of technical aspect

Indicator	Grade	Score
Very low	Very high	5
Low	High	4
Moderate	Moderate	3
High	Low	2
Very high	Very low	1

Table A. 7 Scoring system for flexibility and knowledge level indicator of the technical aspect

Indicator	Grade	Score
Very high	Very high	5
High	High	4
Moderate	Moderate	3
Low	Low	2
Very low	Very low	1

Table A. 8 Scoring of technical indicators for each scenario

Technical		R0	R1	R2	R3	R4	R5	R6	S1	S2	S3
Flexibility/expandability		2	2	2	2	2	2	2	3	3	3
Risk of failure	Damage potential	4	3	4	4	4	4	4	3	2	2
	Capacity of reserve	3	3	3	3	3	3	3	2	2	2
Knowhow level		5	3	3	2	5	3	3	3	2	1

A.1.4 Social

Table A. 9 Scoring system for each sub-indicator of the social aspect

Indicator	Grade	Score
Very low	Very high	5
Low	High	4
Moderate	Moderate	3
High	Low	2
Very high	Very low	1

Table A. 10 Scoring of social indicators for each scenario

Criteria	Indicator	Weighting %	R0	R1	R2	R3	R4	R5	R6	S1	S2	S3
Comfortability	Complexity	6	3	3	3	3	3	3	3	2	1	1
	Oder	5	4	4	4	4	4	4	4	3	3	3
	Nuisance	2	4	4	4	4	4	4	4	1	3	3
Affordability	Extra cost	7	3	3	3	3	3	3	3	2	1	1
Health and hygiene	Risk for microbial infection	18	4	4	4	4	4	4	4	4	3	3

A.2 Characterization factors for LCIA of indicators

Table A. 11Characterization factors for LCIA for selected indicators

Impact category	Global Warming Potential (100 years)	Acidification Potential	Freshwater Eutrophication Potential
Unit	kg CO_2-eq/kg	kg SO_2-eq/kg	kg PO_4-eq/kg
Source	IPCC, 2013	ReCiPe, 2016	ReCiPe, 2016
CO_2	1		
CH_4	34		
N_2O	298		
SO_2		1	
No_x		0.36	0.05
NH_3		1.96	0.11

Table A. 12 Coefficient factor of different forms of energy for primary energy demand

Parameter	Unit	Value	Source
Electricity	kWh/kWh_{el}	2.8	European energy mix DIN V 18599 (12-2011)
Heat	kWh/kWh_{th}	1.1	DIN V 18599 (12-2011)
Diesel	kWh/l	13.0	SFOE,2011 Swiss Federal Office of Energy

Table A. 13 Coefficient factor for primary energy of chemical demand

Parameter	Unit	Value	Primary refe.	Original refe.
N	kWh/kg	13.6	KA1.6	Primärenergieeinsatz (Patyk, S. 167)
Phosphorus P_2O_5	kWh/kg	4.9	KA1.6	Primärenergieeinsatz (Patyk, S. 167)
Phosphorus	kWh/kg	2.1	KA1.6	Source: own calculations, based on datasets from Ecoinvent database (Ecoinvent 2007)
Polymer (acrylamid)	kWh/kg	17.64	CoDiGreen, P 21	
$MgCl_2$ (30%)	kWh/kg	0.392	CoDiGreen, P 21	
$FeCl_3$ (40%)	kWh/kg	0.868	CoDiGreen, P 21	
Natural gas	kWh/kWh	0.336	CoDiGreen, P 21	

Table A. 14 Emission factor in different form of energy

Parameter	Unit	CO_2-eq emission (1)	SO_2-eq (2)
Electricity	kg/kWh	0.563	0.00044
Heat	kg/kWh	0.251	0.00134
Source:	1) DWA-KA1.6, 2017	2) Egle et al., 2014	

A.3 Database for wastewater flow

Table A. 15 Volume and composition of faeces

Parameter		Unit	DWA, NASS, 2015	Meinzinger, 2010	Remy, 2010	URWARE, 2005	DWA-A 272	Tervahauta, 2014	Larsen, 2013	This Study
Volume		lit/(pe.a)	0.14	0.15	0.14		0.14	0.1		**0.14**
Solid	DM	g/(pe.a)	38	40.4	45	53.1	61	30	41	**38**
	oDM	g/(pe.a)	35	34.4	42	46.4				**35**
Organic	BOD	g/(pe.a)	20	19.5		22.6	37	24	12	**20**
	COD	g/(pe.a)	60	50	35	47.2	50	50	31	**60**
	TOC	g/(pe.a)		26.2	21				3.5	
Nutrient (inorganic)	N	g/(pe.a)	1.5	1.7	1.5	1.5	12	1.8	1.5	**1.5**
	P	g/(pe.a)	0.5	0.6	0.5	0.5	1.5	0.5	0.6	**0.5**
	K	g/(pe.a)	0.7	0.7	0.55	1		0.9	0.9	**0.7**
	S	g/(pe.a)	0.2	0.2	0.2	0.16			0.61	**0.2**
Heavy metal	Cd	mg/(pe.a)			0.02	0.01				**0.02**
	Cr	mg/(pe.a)			0.02	0.13				**0.02**
	Cu	mg/(pe.a)			1.5	1.1			1.11	**1.5**
	Hg	mg/(pe.a)			0.02	0.009			8.3	**0.02**
	Ni	mg/(pe.a)			0.2	0.19				**0.2**
	Pb	mg/(pe.a)			0.02	0.04			20	**0.02**
	Zn	mg/(pe.a)			10	10.7			11	**10**
Location			Germany	Germany	Germany	Sweden	Germany	the Netherlands	IWA, London	**Germany**

Table A. 16 Volume and composition of greywater

Parameter		Unit	DWA, NASS, 2015	Meinzinger, 2010	Remy, 2010	Sievers, 2018	URWARE, 2005	DWA-A 272	Tervahauta, 2014	Larsen, 2013	This Study
Volume		lit/(pe.a)	108	105	80	82		75	79		**82**
Solid	DM	g/(pe.a)	71	59.5	120	16.5	71.2	13	55	19	**71**
	oDM	g/(pe.a)	44				41.6				**44**
Organic	BOD	g/(pe.a)	18	17.9		37	33.8	18	27	19	**18**
	COD	g/(pe.a)	47	47.7	60	56	62.4	47	52	51	**47**
	TOC	g/(pe.a)		13.3	18					8.4	
Nutrient (inorganic)	N	g/(pe.a)	1	1	1.3	1.25	1.53	1	1.2	0.9	**1.25**
	P	g/(pe.a)	0.5	0.5	0.5	0.5	0.68	0.5	0.4	0.5	**0.5**
	K	g/(pe.a)	1	1.3	2		0.79		0.8	0.3	**1**
	S	g/(pe.a)	2.9	3.5	7.5		0.46			2.9	**2.9**
Heavy metal	Cd	mg/(pe.a)			0.2		0.05				**0.2**
	Cr	mg/(pe.a)			3		1.3				**3**
	Cu	mg/(pe.a)			20		10.3				**20**
	Hg	mg/(pe.a)			0.02		0.005				**0.02**
	Ni	mg/(pe.a)			2		1.6				**2**
	Pb	mg/(pe.a)			3		1.3				**3**
	Zn	mg/(pe.a)			46		13				**46**
Location			Germany	Germany	Germany	Germany	Sweden	Germany	the Netherlands	IWA, London	**Germany**

Table A. 17 Volume and composition of urine

Parameter		Unit	DWA, NASS, 2015	Meinzinger, 2010	Remy, 2010	URWARE, 2005	DWA-A 272	Tervahauta, 2014	Larsen, 2013	This Study
Volume		lit/(pe.a)	1.37	1.27	1.5		1.5	1.4		**1.37**
Solid	DM	g/(pe.a)	57	45.4	60	20	-	40	58	**57**
	oDM	g/(pe.a)	41	34.8	45	7.4				**41**
Organic	BOD	g/(pe.a)	5	4.9		5	5	5.5	5.8	**5**
	COD	g/(pe.a)	10	9.8	15	8.5	10	11	13	**10**
	TOC	g/(pe.a)		5.3	7				4.3	**0**
Nutrient (inorganic)	N	g/(pe.a)	10.4	9.5	10	11	11	9	11	**10.4**
	P	g/(pe.a)	1	1	1	0.9	1	0.8	0.93	**1**
	K	g/(pe.a)	2.5	2.4	2.6	2.4		0.2	2.6	**2.5**
	S	g/(pe.a)	0.7	0.8	0.8	0.7			1.3	**0.7**
Heavy metal	Cd	mg/(pe.a)			0.0002	0.0005				**0.0002**
	Cr	mg/(pe.a)			0.01	0.01				**0.01**
	Cu	mg/(pe.a)			0.05	0.1			103	**0.05**
	Hg	mg/(pe.a)			0.0004	0.00082			1.9	**0.0004**
	Ni	mg/(pe.a)			0.04	0.011				**0.04**
	Pb	mg/(pe.a)			0.01	0.012			2	**0.01**
	Zn	mg/(pe.a)			0.25	0.3			46	**0.25**
Location			Germany	Germany	Germany	Sweden	Germany	the Netherlands	IWA, London	**Germany**

Table A. 18 Average load of kitchen and garden biowaste

Parameter		Unit	Kitchen biowaste	Garden biowaste
Volume		kg/(pe.a)	0.22	0.49
Solid	**DM**	g/(pe.a)	80	123
	oDM	g/(pe.a)	36	87
Organic	**TOC**	g/(pe.a)	13	45.5
Nutrient (inorganic)	**N**	g/(pe.a)	0.9	1.4
	P	g/(pe.a)	0.2	0.6
	K	g/(pe.a)	0.6	13.6
	S	g/(pe.a)	0.1	0.06

Source: Remy, 2010

A.4 Technical data of different toilets

Table A. 19 Characteristic of different toilets

Parameter	**Water demand (lit/pe.a)**					**Cost (€)**	**Life span (year)**
Toilet type	Remy, 2010	Meinzinger, 2010	Tervahauta, 2013	Kujawa-Roeleveld, Zeeman, 2006	This study	Meinzinger, 2010	Meinzinger, 2010
Conventional toilet	24-36	30	34	36-72	30	250-300	20
Conventional low flush (two buttons)				14	14		20
Vacuum toilet	5.2-24	6	6		6	600-980	20
Urine diversion toilet (gravity)			5	5-7	5	450-950	20
Urine diversion toilet (vacuum)			2	3-6	2	700-1500	20

A.5 Equation of material flow

Table A. 20 Material flow equations for base of each process unit

Influent	**q*(1-(outpct_sl)/100)**
Nitrogen	n*(1-(alfa_N_sl)/100)/(1-(outpct_sl)/100)
Phosphorus	p*(1-(alfa_P_sl)/100)/(1-(outpct_sl)/100)
COD	cod*(1-(alfa_COD_sl)/100)/(1-(outpct_sl)/100)
DM	res1*(1-(alfa_Res1_sl)/100)/(1-(outpct_sl)/100)
oDM	res2*(1-(alfa_Res2_sl)/100)/(1-(outpct_sl)/100)
Sludge/ or other output	q*outpct_sl/100
Nitrogen	n*alfa_N_sl*(gamma_N/100)/outpct_sl
Phosphorus	p*alfa_P_sl*(gamma_P/100)/outpct_sl
COD	cod*alfa_COD_sl*(gamma_COD/100)/outpct_sl
DM	(res1*alfa_Res1_sl*(gamma_Res1/100)/outpct_sl)
oDM	(res2*alfa_Res2_sl*(gamma_Res2/100)/outpct_sl) +TS_p
Energy	((Eend_COD_elim*COD_elim) +(Eend_N_elim*N_elim)+(Eend_P_elim*P_elim))* 365/1000+Eend_spec*q*365+(Eend_spec_PE*numunits*pop*pppp)

Capital cost	capex_total_0*numunits*pppp
Capital cost-material	capex_material_0*numunits*pppp
Capital cost-planning	capex_planning_0*numunits*pppp
Capital cost-construction	capex_constr_0*numunits*pppp
Operation cost	opex_specv*q*365+opex_spect_PE0*pop*pppp
Water supply	water_0*q*365
material demand	cons_precip_0*q*res2*(365/1000000)
Transport	lorry_11_0*numunits*pppp
Emission	direm_PO4_PE*pop*pppp

Emission	direm_CH4_PE*pop*pppp
Emission	direm_N2O_PE*pop*pppp
Emission	direm_CO2_PE*pop*pppp
Emission	direm_NH3_PE*n*q*1/1000*365
Emission	direm_cod_PE*pop*pppp
Emission	direm_ntot_PE*pop*pppp
Emission	direm_ptot_PE*pop*pppp
Saving of CO2 emission by substituting by-product of sludge with mineral fertiliser	((uq*1000*CO2_emiss_rate*365) *(-1))
Saving of N2O emission by substituting by-product of sludge with mineral fertiliser	uq*1000*N2O_emiss_rate*365*-1
Saving of energy demand by substituting by-product of sludge with mineral fertiliser	uq*1000*sub_rate_ende*365*-1
Capital gain	capgain_Q_0*Q*365*(-1)
N-recovered	((percNrecovery/100) *Q*365/1000)/8
P-recovered	((percPrecovery/100) *Q*365/1000)/8

A.6 Transport distances

Table A. 21 The average distance for transport in different sections of wastewater process (km)

Parameter		Frishknecht et al., 1996	Bengtsson et al., 1997	Reckerzügl, 1997	Frishknecht and Jungbluth, 2002	Jönsson et al., 2004	Tidaker et al. (2007)	Remy, 2010	This Study
Wastewater	Household to treatment facilities						10		**10**
Fertiliser	Mineral fertiliser		1200		600			300	**300**
	Sewage sludge		25	30				20	**20**
	Compost to composting							20	**20**
	compost to farms		2	30				20	**20**
	Faeces to composting							20	**20**
	Digester residual	20	25	30		30		20	**20**
	Urine to treatment							5	**5**
	Urine to farm		8			30		20	**20**
Waste	Sludge to incineration	30		20				30	**30**
	Biowaste to incineration							30	**30**
Chemicals	Flocculation	50	1200					300	**300**
Construction materials	Concrete to site			57	50			50	**50**
	Concrete to disposal							50	**50**
	Other material to the site			57	200			300	**300**
	Other material to the disposal							100	**100**

A.7 Technical data of Vacuum system

Table A. 22 The overview of energy demand for vacuum system

System	discharge of wastewater (lit/(pe.a))	Population (pe)	Energy demand (kWh/(pe.a))	Remarks	Source
Flintenbreite	5	108	51	Not working to capacity	Otterwasser, 2005
Vauban	8,4	40	7		Schneidmadl, 1999
Hannover	9	80	27	Annual period	Herrmann and Hesse, 2002
Stahnsdorf	9	9	3.1	Calculated	Peter-Fröhlich et al., 2007
ATV (DWA)	150	-	36	Combined wastewater	ATV, 1995
Remy	5.8	5000	15	Calculated	Remy, 2010
DESARA	-	-	25	Calculated	Kujawa, 2005

A.8 Cost data

Table A. 23 Cost of used resources and materials

	Parameter	Value	Unit	Source	Remark
Energy	Electricity	0.17	€/kWh	Lengemann, 2018	
	Heat	0.01	€/kWh	DESTATIS, 2017	
	Natural gas	0.035	€/kWh	Egle, 2014	
	Fuel diesel	1.4	€/L	Egle, 2014	
	Oil	0.5	€/L	Egle, 2014	
	Coke	360	€/t	Egle, 2014	
Chemical	$Ca(OH)_2$	90	EUR/t	Herrmann, 2017	Concentration 90%
	$CaCO_3$	150	EUR/t	Estimation	Concentration 100%
	H_2SO_4	160	EUR/t	Miehe et al., 2013	Concentration 96%
	HCl	139	EUR/t	Herrmann, 2017	Concentration 32%
	HNO_3	400	EUR/t	Herrmann, 2017	Concentration 68%
	$MgCl_2$	80	EUR/t	Herrmann, 2017	Concentration 30%
	MgO	600	EUR/t	Ewert und Kalauch, 2018	approx.100%
	NaOCl	130	EUR/t	Miehe et al., 2013	Concentration 100%
	NaOH	180	EUR/t	Miehe et al., 2013	Concentration 32%
	Na_2S/ CaS	800	EUR/t	Herrmann, 2017	Concentration 60%
	Citric acid	750	EUR/t	Herrmann, 2017	Concentration 50%
	Magnesium hydroxid $Mg(OH)_2$	230	EUR/t	Egle, 2014	
	Sulfruic acid H_2SO_4	150	EUR/t	Egle, 2014	Concentration 98%
Product	Additive salt (Fe-/ AlClx)	135	EUR/t	Lengemann, 2018	-
	H_3PO_4 (fertiliser)	560	EUR/t	Herrmann, 2017	Concentration 70%
	P_2O_5	700	EUR/t	Agrarheute, 2018	Concentration 100%
Disposal	Sludge	80	EUR/t	Staub, 2018	
	Ash	40	EUR/t	Schäfer, 2017	
	Wastewater treatment	2	EUR/m^3	Egle, 2014	
	Sludge mono-incineration	400	EUR/t DM	Egle, 2014	
Further factors	Polymer (dewatering)	3,000	EUR/t	Lengemann, 2018	
	Process water	2.5	EUR/t	Miehe et al., 2013	
	O_2	80	EUR/t	Egle, 2014	
	Personal	60,000	EUR/a	geschätzt	

* Data is adapted from Kraus et al., 2019

Table A. 24 Monetary value of pure nutrients

Nutrient	Egle, 2014 (€/kg)	Stäudel, 2017 (€/kg)
P	2.3	1.81
N	1.1	0.87
K	0.9	0.67

Table A. 25 Revenue of by-products from nutrient recovery

Product	Revenue (€/t)	Source *
$(NH_4)_2\ SO_4$	30	Herbst, 2008
N fertiliser	58	Meinzinger, 2010
MAP	100-250	Herbst, 2008
P fertiliser from ash	170-270	Ante, 2009
P fertiliser	1500	Meinzinger, 2010

*Data is adapted from Meinzinger, 2010

A.9 Overview of selected process units for source separated flow

A.9.1 Assessment of different greywater treatment systems

Table A. 26 Functional data of process units for greywater treatment

Process unit	Parameter	Removal efficiency of each process		
		Physical	Biological	Chemical
SBR	COD	15	93	-
	N	11	96 [1]	-
	P	10	0	86 [2]
	K	0	no data	no data
Soil filter	COD	15	90	-
	N	11	96 [1]	-
	P	10	50	86 [2]
	K	0	no data	no data
MBR	COD	15	93	-
	N	11	96 [1]	-
	P	10	0	95 [2]
	K	0	no data	no data

1: including nitrification and denitrification

2: By adding Fe

Energy demand for greywater is calculated based on energy demand for nutrient removal (see Table 19)

Table A. 27 Mass balance of nutrient in process units for greywater treatment

	Parameter		Effluent*	Sludge*	Air*
SBR	**COD**	COD-C	5.8		
		CO_2-C			78.2
		CH_4-C			
		C-organic		16	
	N	N dissolved	27.7		
		N_2-N			39.5
		NH_3-N			0.3
		N_2O-N			0.2
		N sludge		32.3	
	P	-	9.3	90.7	
	K	-	100		
Soil filter	**COD**	COD-C	8.5		
		CO_2-C			76.5
		CH_4-C			
		C-organic		15	
	N	N dissolved	53.4		
		N_2-N			30.9
		NH_3-N			0.3
		N_2O-N			0.2
		N sludge		15.2	
	P	-	45	10	
	K	-	100		
MBR	**COD**	COD-C	6		
		CO_2-C			82.4
		CH_4-C			
		C-organic		11.6	
	N	N dissolved	36.4		
		N_2-N			30.7
		NH_3-N			0.3
		N_2O-N			0.2
		N sludge		32.4	
	P	-	4.6	95.4	
	K	-	100		

Source: LCA model, TU Berlin, Remy, 2010

*Value is based on %

4.2% of N uptakes by plants

45% stays in the filter material

A.9.2 Assessment of different urine treatment systems

Table A. 28 Overview of selected urine treatment process unit

Target	Technology	Parameter	Product	Residual	Additional input
Hygienisation	Storage	C	99	1	
		N	99	1	
		P	80	20	
		MP	98	2	
Volume reduction	Evaporation	C	99	1	Energy: 108 kWh/m^3
		N	95	5	
		P	100	0	
		MP	100	0	
	Freeze-thaw	C	#	#	Energy: 297 kWh/m^3
		N	80	20	
		P	80	20	
		MP	#		
	Reverse osmosis	C	60	40	Acid (no data for dosage)
		N	85	15	
		P	2	98	
		MP	8	92	
Stabilisation	Acidification	C	100	0	Acid: 60 mole H^+/m^3
		N	100	0	

		P	100	0	
		MP	100	0	
	Nitrification	C	18		Energy aeration: 14.58 kWh/m^3
		N	100	0	
		P	100	0	
		MP	#		
Nutrient removal	Anammox	C	100	0	Oxygen
		N	20		Energy aeration: 14.58 kWh/m^3
		P	100	0	
		MP	#	#	
Handling of micropollutants	Electrodialysis	C	10	90	Energy: 8.1 kWh/m^3
		N	10	90	
		P	10	90	
		MP	90	10	
	Nanofiltration	C	60	40	Energy: 6 kWh/m^3
		N	85	15	
		P	2	98	
		MP	8	92	
	Ozonation	C	#	#	Oxidant
		N	100	0	
		P	100	0	
		MP	0	0	

Source: Höglund et al. 2002; Maurer et al. 2006; Tettenborn 2011; Randall und Naidoo 2018

A.9.3 Assessment of different blackwater treatment systems

Table A. 29 Anaerobic treatment systems for the treatment of vacuum-collected blackwater

Parameter	Unit	CSTR	AC system	UASB septic tank	UASB septic tank	UASB
		Wendland et al. (2007)	Kujawa-Roeleveld et al. (2006)	Kujawa-Roeleveld et al. (2006)	Meulman et al. (2008)	de Graaff et al, (2010)
Temperature	°C	37	20	25	25	25
Reactor volume	lit	10	200	200	7200	50
Inflow concentration		8.7	10	12.3	16.1	7.7-9.8
COD removal	%	61	80	78	87	73
HRT	d	20	150	29	30	8.7
SRT	d	20	150	>365	>365	254
Methane	[NL·p−1·d−1]	9	10.2	14	13	10
Methane	[Nm^3·m−3 Influent]	1.9	2.1	2.1	2	1.8
Methanization (5)	%	60	58	60	57	54
Loading rate	[kgCOD·m−3·d−1]	0.44	0.3	0.42	0.36	1

*Adapted from de Graaff et al. 2010

A.9.4 Thermal energy balance for hygienisation process

Table A. 30 Parameter for the thermal energy balance for hygienisation process

Specific heat capacity of dry matter	**0.00105**	**MJ/(Kg*K)**	**MURL, 1999**
Specific heat capacity of water	0.00416	MJ/(Kg*K)	
Hygienisation temperature	70	°C	Retention time: 1h
Starting temperature of the substrate (annual mean)	15	°C	Assumption
Substrate temperature after the heat exchanger	35	°C	
Proportion of the recovered waste heat from output	85	%	Assumption
Energy losses through transmission	5	%	According to sludge digestion (MURL, 1999)

*Adapted from Remy 2010

A.10 Phosphorus recovery from different stages of wastewater treatment

A.10.1 Overview of phosphorus recovery technologies

Table A. 31 List of different technologies for phosphorus recovery

Process	Technic	Location/operator	scale	Product	Reference
P recovery from digested sludge	AirPrex®	Waßmannsdorf (DE) BWB	full	MAP Berliner Pflanze	http://www.nutrientplatform.org/business-cases/bedrijfsnaam/a-tm-z/ 41-waternet.html
	AirPrex®	MG-Neuwerk (DE) Niersverband	full	MAP	
	AirPrex®	BS-Steinhof (DE) SE|BS / AVB	full	MAP/Sludge	
	AirPrex®	Wieden-Echten (NL)	full	MAP	
	AirPrex®	Amsterdam (NL) planned	full	MAP	
	LYSOGEST®	Lingen (DE) SE Lingen	full	MAP	http://beta.eliquostulz.com/de/lysogest.html
	NuReSys®	Leuven (BE) Aquafin	full	MAP BIOSTRU®	http://www.nuresys.org/content/references
	PHOSPAQ	Olburgen (NL) Waterstromen	full	MAP	Abma, W.R., W. Driessen, R. Haarhuis enVan Loosdrecht, M.C.M. (2010) Upgrading of sewage treatment plant by sustainable and cost-effective separate treatment of industrial Water Science & Technology, 61(7), pp. 1715–1722 wastewater.
	PHOSPAQ	Lomm (NL) Waterstromen	full	MAP	
	CRYSTALACTOR®	Geestmerambacht (NL)	full	CaP	http://www.nhm.ac.uk/research-curation/research/projects/phosphate-recovery/Nordwijkerhout/Piekema.pdf
	Gifhorn process	Gifhorn (DE) ASG	full	MAP	http://www.asg-gifhorn.de/docs/2007-08-flyerklaerschlammbehandlungsanlage.pdf

	Fix-Phos	Hildesheim (DE) SEHi	full	CaP/Sludge	Petzet and Cornel (2012)
	Stuttgart process	Offenburg (DE)	pilot	MAP	http://www.recyclingmagazin.de/rm/news_detail.asp?ID=15423&SID=617061192168100100&NS=1
	Budenheim process	Mainz (DE)	pilot	CaP	Schnee (2014)
P recovery from sludge liquor/process water	REPHOS®	Altentreptow (DE) Remondis Aqua	full	MAP	http://www.remondis-aqua.de/aq/industrie/leistungsspektrum/abwasserbehandlung/leistungen/
	PEARL® (PEARL 500)	Slough (UK) Thames Water	full	MAP Crystal GreenTM	http://www.ostara.com/sloughUK
	NuReSys® (prototype)	Dairy processing (BE)	full	MAP BIOSTRU®	http://www.nuresys.org/content/references
	NuReSys®	Potato processing (BE)	full	MAP BIOSTRU®	
	P-RoC	Neuburg (DE)	pilot	CaP	http://kit-neuland.de/2012/uebersicht/die-phosphor-philosophie/
	PHOSTRIP	Brussels-North (BE) Aquiris (Veolia Eau)	pilot	MAP or CaP	Schoumans, Bouraoui et al. 2015 – Phosphorus management in Europe
P recovery during or after incineration	MEPHREC®	Nürnberg (DE) SUN	full	P fertiliser	http://www.nuernberg.de/internet/klaerschlammverwertung/
	SUSAN	Koenigs Wusterhausen (DE) RETERRA	full	P fertiliser	http://www.outotec.com/en/Products–services/Energy/Phosphorus-recovery/
	Thermphos*	Vlissingen (NL)	full	White P4	Schipper and Korving (2009)
	LeachPhos	MSWI plant of Bern (CH)	pilot	MAP or CaP	http://www.bsh.ch/de/news/news-detail.aspx?nwsid=9
	EcoPhos/SNB/HVC	EcoPhos Belgium	full	DCP	http://www.ekobalans.se/en/kretslopp/i-helsingborgs-stad.html

* Adapted from Kabbe (2013) and Stemann et al. (2014)

A.10.2 Technologies for P recovery from sludge and sludge liquor

Table A. 32 Technical data for P recovery from sludge and sludge liquor

Parameter	unit	Sludge precipitation	liquor precipitation 1	liquor precipitation 2	Sludge leaching 1	Sludge leaching 2
Reference system		EBPR	EBPR	EBPR	EBPR	EBPR
Input material		Digested sludge	sludge liquor	sludge liquor	Digested sludge	Digested sludge
P recovery[1]	%	7.2	11.8	11.4	48.7	45
Electricity[2]	kWh/m³	0.92	0.36	0.2	4.2	2.7
Heat	kWh/kg Pout	-	1.8	0.9	-	-
$MgCl_2$ (30%)	L/m³	3.4	1.3	1.3	-	-
	Mg/P3	2.1	1	1	0.2	-
$Mg(OH)_2$ (53%)	L/m³	-			0.1	1
	Mg/P3				-	1
MgO (100%)	kg/m³	-			2.3	2
	Mg/P3	-			3.7	5
NaOH (50%)	L/m³	-			2.7	-
H_2SO_4 (78%)	L/m³	-			-	3.6
Na_2S (15%)	L/m³	-			-	
Citric acid (50%)	L/m³	-			1%	
Dewatering		+2% DM			-	
Polymer demand		-25%			-	
Concentration of chemicals as Mass-%, related to m³ input (sludge or liquor)						
1 related to total P load in raw sludge (= 100%)						
2 related to input flow (sludge or liquor)						
3 molar ratios between Mg and dissolved PO_4-P						

* Adapted from Remy (2015)

A.10.3 Technologies for P recovery from dried sludge and ash

Table A. 33 Technical data for P recovery from dried sludge and ash

Parameter	unit	Sludge metallurgic[1]	Ash metallurgic[2]	Ash leaching 1	Ash leaching 2	Ash thermo-chemical[5]
Reference system		ChemP	ChemP	ChemP	EBPR	EBPR
Input material		Dried sludge	Ash	Ash	Ash	Ash
P recovery[2]	%	80.5	80.5	70.1	97	98
Electricity demand[3]	kWh/kg	0.36/0.34	0.09	0.11	0.03	0.14/0.126
Electricity output[3]	kWh/kg	0.32/0.454	-	-	-	-
Heat demand[7]	kWh/kg	0.6/04	-	-	-	0.26
Natural gas	kWh/kg	-	-	-	-	0.06/0.046
Coke	kWh/kg	0.7	1.5	-	-	-
Steam	kg/kg	-	-	-	3	-
$Ca(OH)_2$ (100%)	kg/kg	-	-	0.26	-	0.015
H_2SO_4 (78%)	L/kg	-	-	0.28	-	-
NaOH (50%)	L/kg	-	-	0.05	-	0.014
HCl (37%)	L/kg	-	-	-	0.9	-
$NaSO_4$ (100%)	kg/kg	-	-	-	-	0.37
Dolomite (100%)	kg/kg	0.04	-	-	-	-
O_2 (liquid)	kg/kg	0.023	0.032	-	-	-
Ion exchange resin	g/kg	-	-	-	0.29	-
Product: Fe slag	kg/kg	0.057	0.146	-	-	-
Product: $CaCl_2$ (100%)	kg/kg	-	-	-	0.67	-
Product: $FeCl_3$ (40%)	kg/kg	-	-	-	0.41	-
Concentration of fuels and chemicals as Mass-%, related to input (dried sludge briquettes (14kt/a) or ash)						
1 including sludge drying (80% DM)						
2 related to total P load in raw sludge (= 100%)						
3 related to input flow (sludge or liquor)						
4 for integrated option in MSWI plant						
5 including partial drying of 6% of sludge as reducing agent						
6 for integrated option with mono-incineration plant						
7 for sludge drying, covered by additional natural gas						

* Adapted from Remy (2015)

A.11 Organic and mineral fertiliser consideration

Table A. 34 Potential nutrient uptake from organic fertiliser

Parameter	Nitrogen	Phosphorus	Potassium	Source	This study
	% of N total	% of P total	% of total K		**N/P/K**
Sewage sludge	10-63/50/50	20-70/70/70	100/-/100	1/2/3	**50/70/100**
Urine	90-100/60-90/80-90/90	-/80-120/-/100	-/-/-/100	4/2/5/3	**90/100/100**
Stabilised digester residual	20-60/30	-/100	-/100	7/3	**30/100/100**
Liquid digester residual	100/90	100/100	100/100	8/3	**90/100/100**

1) Schneidmadl, 1999 (literature review)
2)Bengtsson et al., 1997 (including volatilisation of nitrogen during storage and handling)
3)Remy, 2010
4)Peter-Fröhlich et al., 2007
5)Stockholm Vatten, 2000
6)Stadtmüller, 2004
7)Roschke, 2003
8)Jönsson et al., 2004

Table A. 35 Emission of sludge application in agriculture

Parameter		Unit	Value
Emission (Air)	NH_3	g/kg N in sludge	130
	N_2O	g/kg N in sludge	16
	No_x	g/kg N in sludge	40
Emission (Water)	NO_3	g/kg N in sludge	79
	PO_4	g P_2O_5/kg P_2O_5 in sludge	50

Source: Kraus et al., 2019

Table A. 36 Nitrogen emission of urine treatment process units

Emission	Application	This study	Source
	% N in urine	% N in urine	
NH_3-N	2-10/5/3-10	10	1/2/3
N_2O-N	1.25/1.25/0.3	1.25	2/4/3
No_x-N	0.1/0.7	0.7	4/3

Source: 1) Johansson et al., 2001 2) Tidaker, 2003 3) Muskolus, 2008
4) EMEP/CORINAIR, 2004 (equivalent to mineral fertilisers)

A.12 Evaluation of reference scenario

A.12.1 Cumulative energy demand

The total cumulative energy demand of all involving processes in the study area of Wassmannsdorf in 2009 amounts to 547MJ/(pe.a) (Figure A.1). The 69% of total energy is used in the form of electricity (375 MJ/(pe.a) as the primary contributor, thermal energy (48 MJ/(pe.a)) is provided internally by CHP plant, natural gas for sludge drying (57 MJ/(pe.a)) and fuel oil (21 MJ/(pe.a)) for the operation of the mono-incineration.

Chemical demand for the process of secondary treatment (6 MJ/(pe.a)), dewatering 16 MJ/(pe.a) and $MgCl_2$ in MAP precipitation (4 MJ/(pe.a)) and transport of sludge to disposal (19MJ/(pe.a)) has a small role for the total energy demand.

The highest energy demand originates from the biological wastewater treatment for aeration (251 MJ/(pe.a)), which belongs to the treatment plant's liquid phase. The 8% of total energy demand is the treatment of return liquor from thickening, dewatering, and drying.

Considering the energy demand of the sludge treatment line, the operation of the digester has the highest energy demand for heating. However, the heat demand is easily substituted by generated heat from the CHP plant. Thickening and dewatering require 75 MJ/(pe.a) or 25% of total energy demand in the sludge treatment line, mainly for electricity and chemical demand. Despite it, only 40% of digested sludge is effectively dried; this process requires 57 MJ/(pe.a) which is 13% of the total energy demand.

Considering the substitute of the different by-products of treatment processes including electricity and heat generation from CHP plant, mono-incineration, substitute of fossil fuel with dried and dewatered sludge, substitute of MAP precipitation as fertiliser from P, the net of energy is estimated 123 MJ/(pe.a) (Figure A.2). It proves the energy benefit from biogas production, MAP precipitation, and co-incineration of sludge is more than the total cumulative energy demand. A significant part of energy recovery is related to biogas production in the digester and, consequently, the efficiency of the CHP plant (42% electricity and 33% heat). Substitute dewatered, and dried sludge with lignite in power plants and hard coal in cement plants save 11% and 9% energy, which are supplied from fossil fuel. The recovered energy from the substitute of MAP product with mineral fertiliser is only 2% of total recovered cumulative energy.

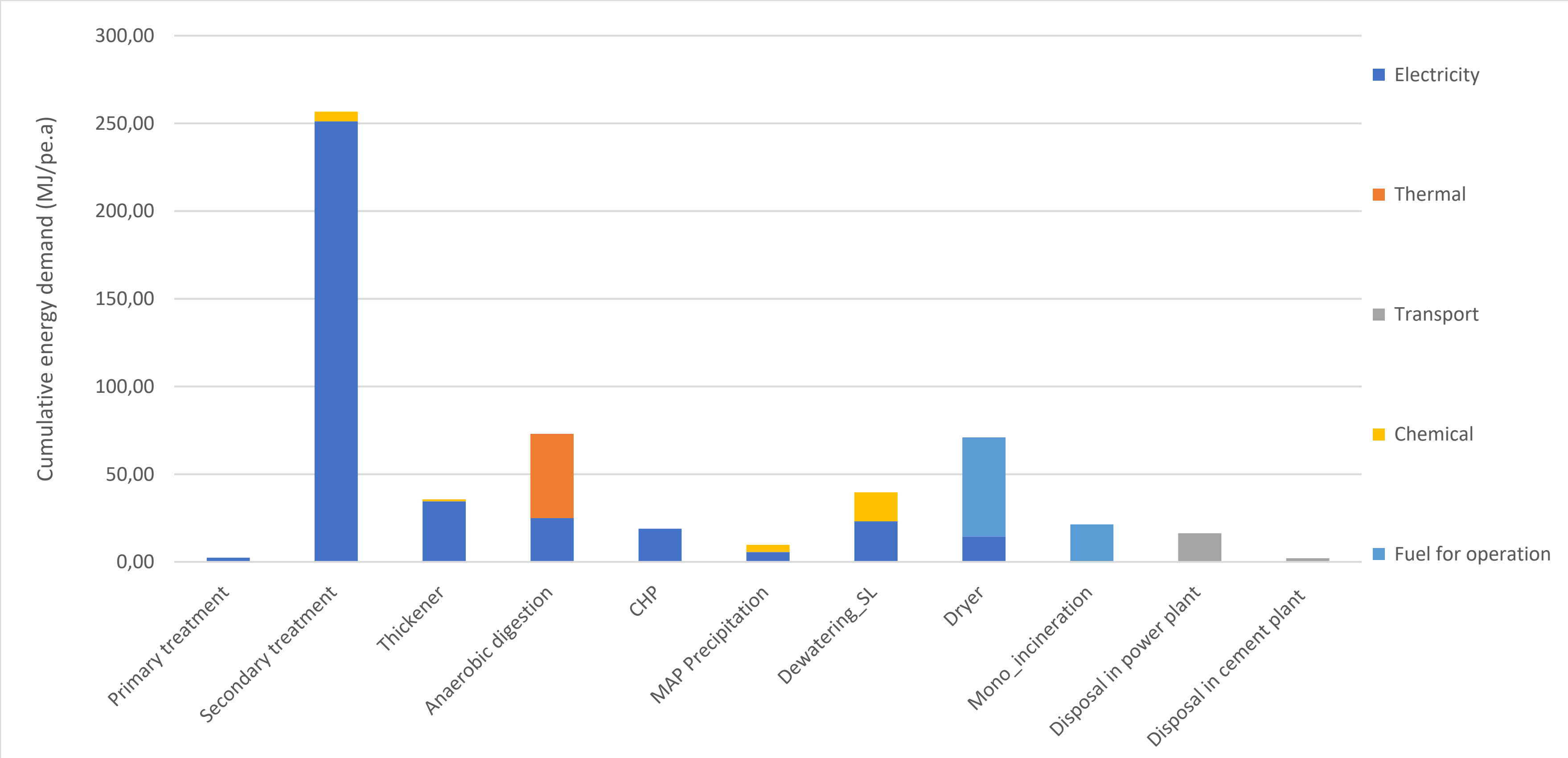


Figure A. 1 Cumulative energy in Wassmannsdorf treatment plant

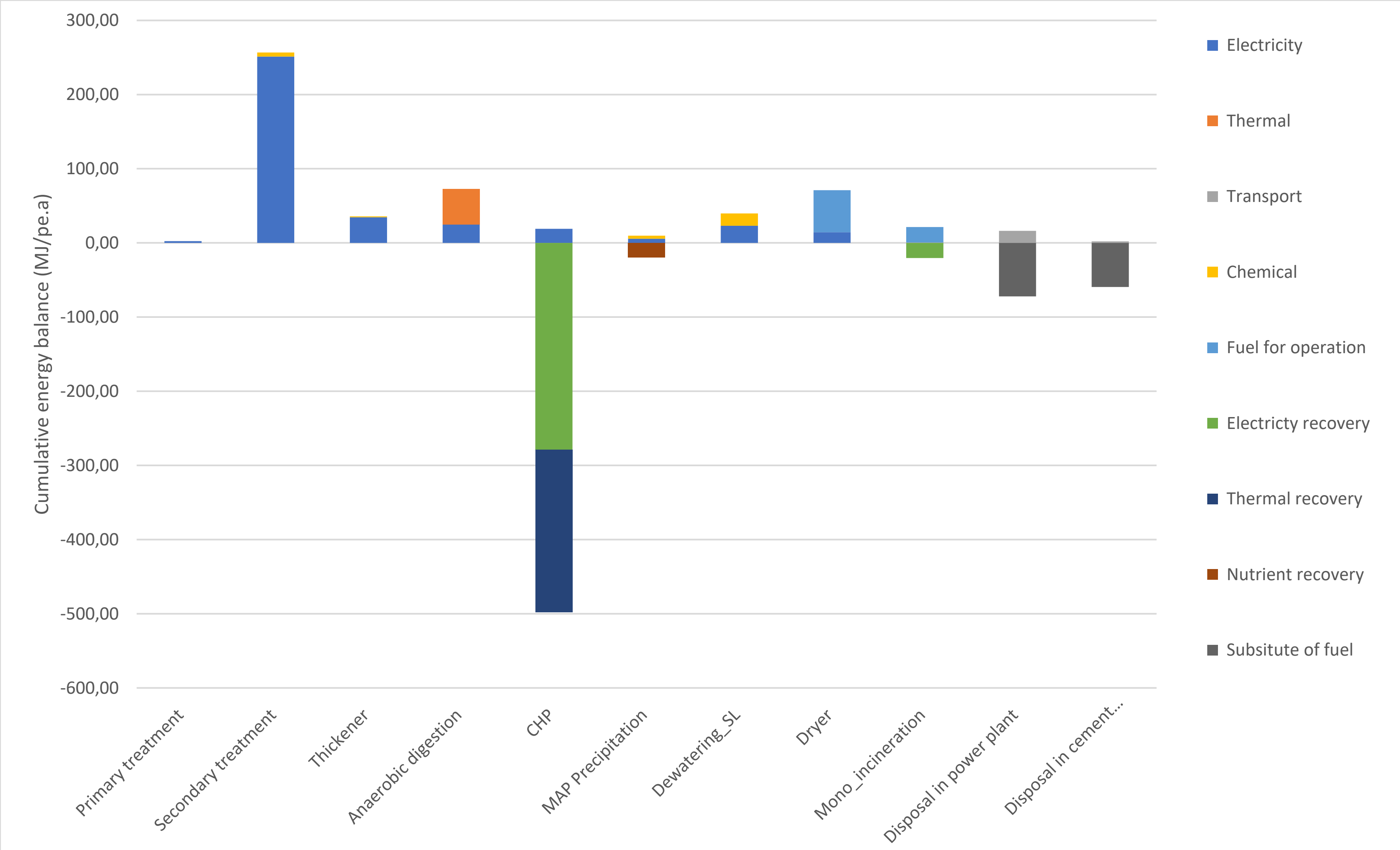


Figure A. 2 Cumulative energy in Wassmannsdorf treatment plant

A.12.2 Global Warming Potential

The total global warming potential of all involving processes in the study area of Wassmannsdorf in 2009 amounts to 27kg CO_2/(pe.a) (Figure A.3). The major contributor to GWP is the supply of electricity for the biological treatment (58% of total GWP); heat with 8%, transport of disposed of sludge 2%, and chemical production with 2% have a minor contribution for the emission of greenhouse gases. However, these emissions are not taking place on the wastewater treatment plant and counting as an indirect emissions.

Whereas direct emission originates from the CO_2 emission of burning natural gas in the drying process (2.86 kg CO_2/(pe.a)) or fuel oil in mono-incineration (1.40 kg $CO_{2\text{-}eq}$/(pe.a)). N_2O emission is generated from biological N removal (6 kg $CO_{2\text{-}eq}$/(pe.a)), sludge incineration (1 kg $CO_{2\text{-}eq}$/(pe.a)). CH_4 is generated from CHP plant (0.5 kg $CO_{2\text{-}eq}$/(pe.a)).

The direct emission of CO_2 with 11% and N_2O with 18%, and CH_4 with 2% contribute to the global warming potential. This contribution of greenhouse gases can be applied in optimising the process by decreasing the high-demand section of treatment processes. [to make more discussion here or in next chapter for interpretation]

By accounting for the substitute of the by-product of different processes, the net global warming potential is reached to -9 $CO_{2\text{-}eq}$/(pe.a) (Figure A.4). It shows that the overall process has a negative global warming potential, meaning that replacing dewatered/dried sludge with fossil fuel can compensate for the emission from processes.

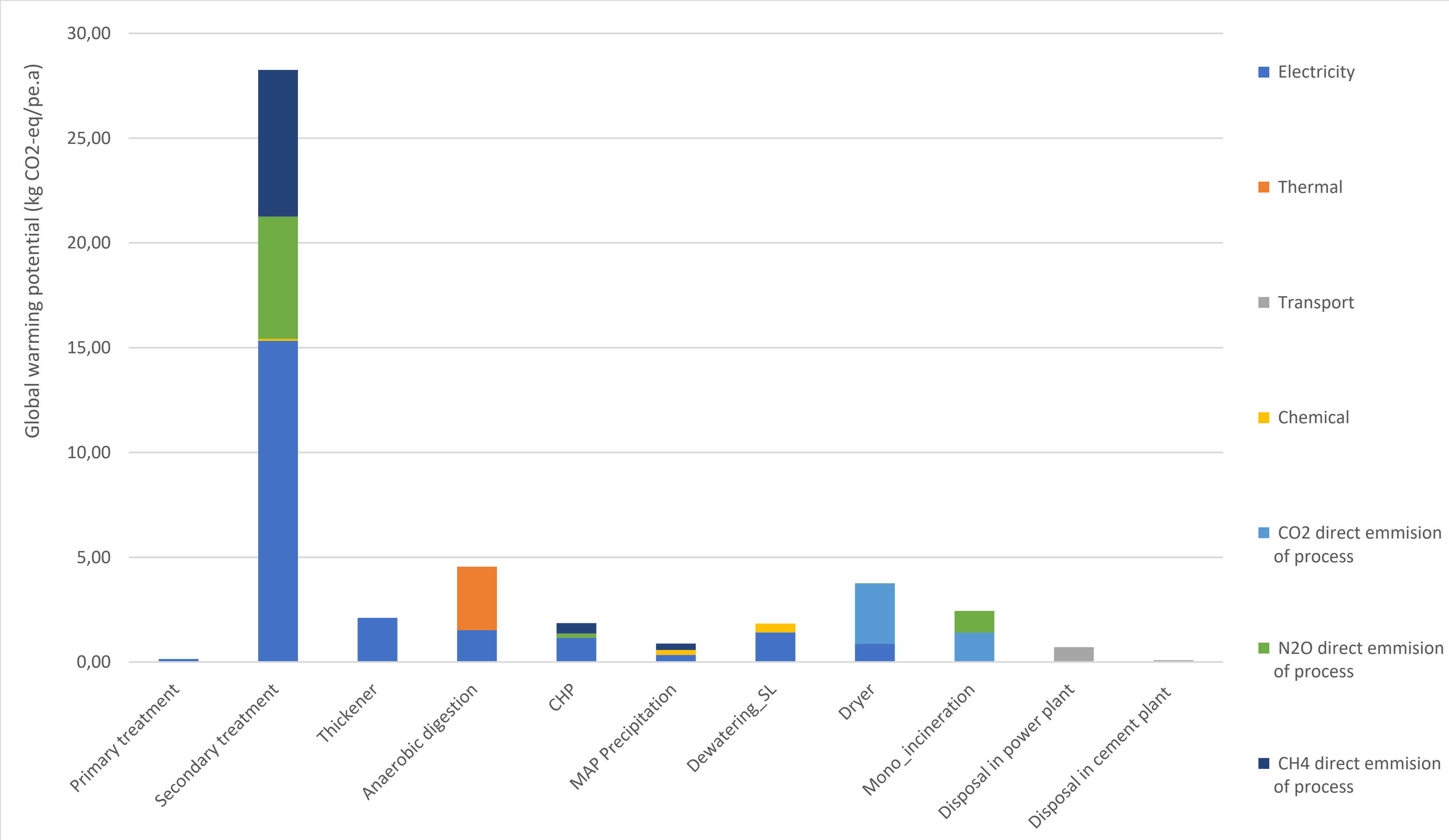


Figure A. 3 Global warming potential in Wassmannsdorf treatment plant

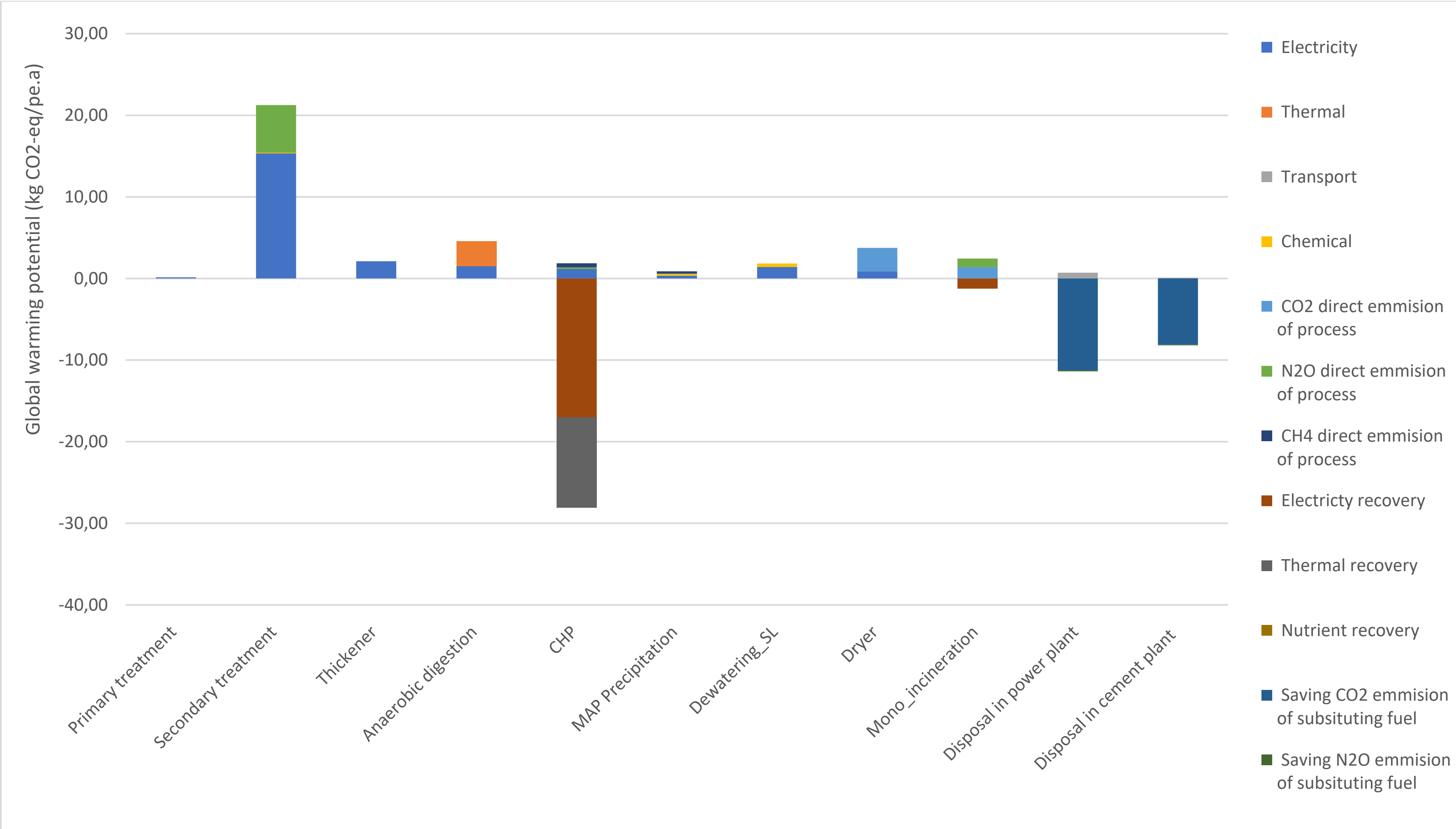


Figure A. 4 Global warming potential in Wassmannsdorf treatment plant

A.12.3 Eutrophication of freshwater and seawaters

Eutrophication of freshwater is caused by direct and indirect emissions of P into surface waters. The total EP $_{fresh}$ amounts to 78 g P-eq/(pe.a) for Wassmannsdorf and mainly originated from wastewater effluent. The substitution of mineral fertiliser with the by-product of the treatment plant has a minor role in reducing the impact of this indicator. The positive side-effect of precipitating P from sludge is the considerable reduction of P in return load to the mainstream wastewater treatment plant and consequently the direct emission of P from effluent in surface water.

The eutrophication of seawater is considered by accounting for the emission of nitrogen and organic matter (as COD). The total amount of $EP_{seawater}$ is 196 gN-eq/(pe.a). Nitrogen can be eliminated by biological wastewater treatment and primarily by applying by-products of sludge treatment in agriculture.

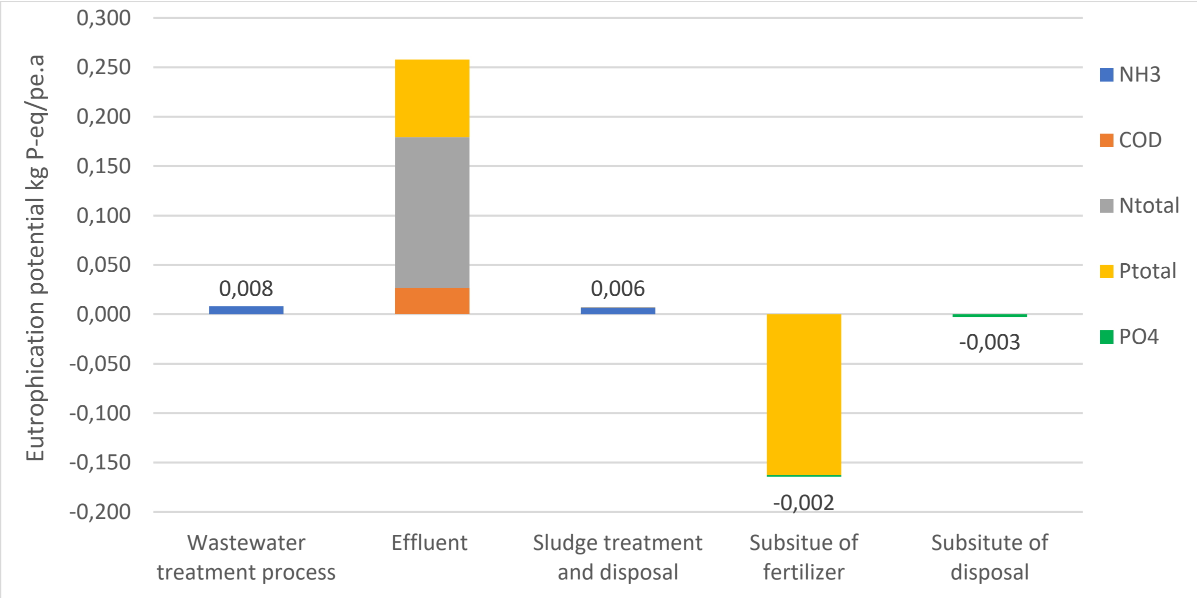


Figure A. 5 Eutrophication potential for fresh and seawater of Wassmannsdorf treatment plant

A.12.3 Acidification

The net acidification potential of the Wassmannsdorf treatment plant amounts to 32.3 g SO_2-eq/(pe.a) (Figure A.6). The major contribution to acidification potential is from the emissions of acidifying gases (NH_3, NO_x, and SO_2) in biological wastewater treatment by 84% direct emission of NH_3 and 15% of indirect emission of SO_2 by required electricity demand. The direct emission of NH_3 is occurred during the ammonification/deammonification process and cannot be avoided altogether. It can only be optimised by accurate control of the aeration process. The substitute of by-product (sludge) as fertiliser saves 4 g SO_2-eq/(pe.a) of acidifying gases.

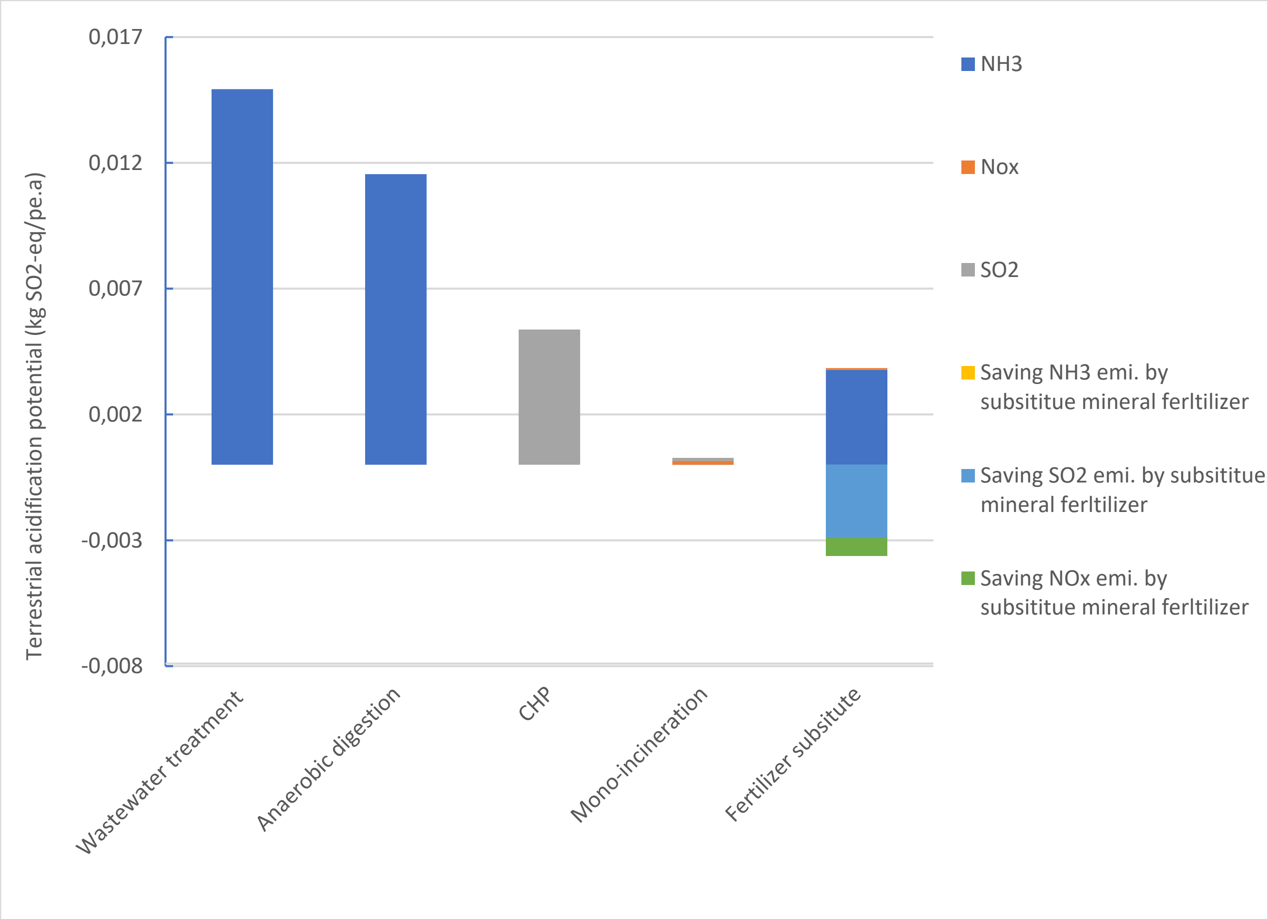


Figure A. 6 Acidification potential in Wassmannsdorf treatment plant

A.13 Model validation and calibration

The validation and calibration process has been done based on the results of Stahnsdorf project and the assessment of LCA by Remy for this project.

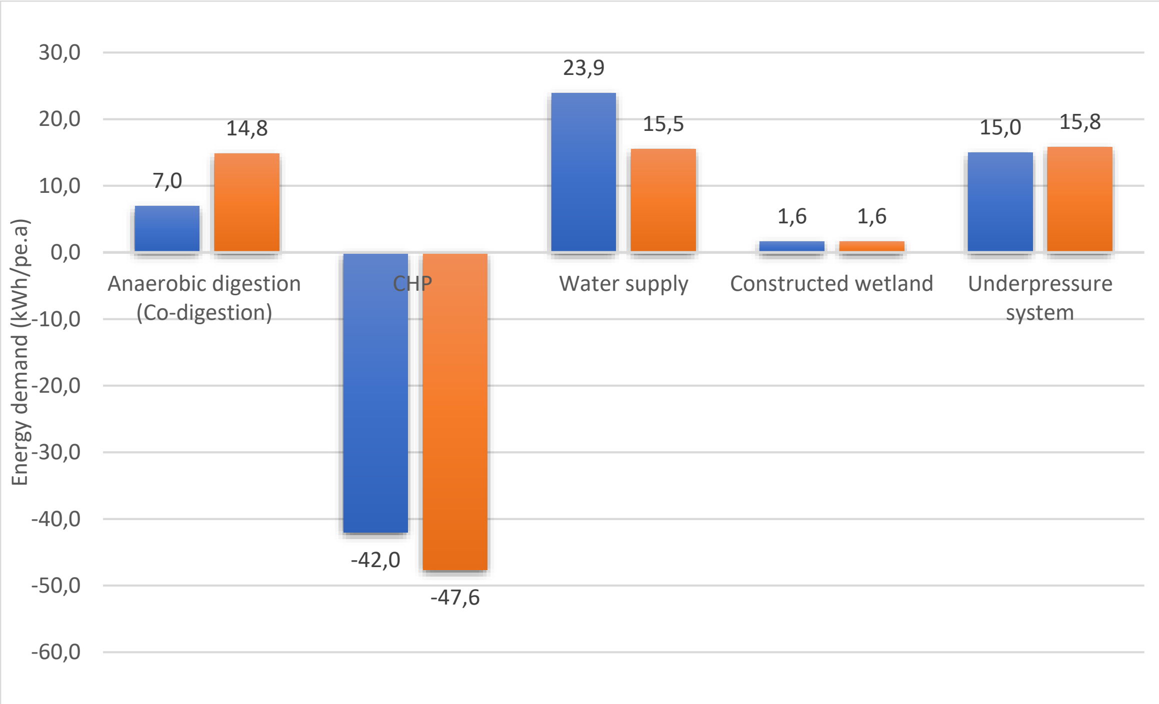


Figure A. 7 Validation of energy demand

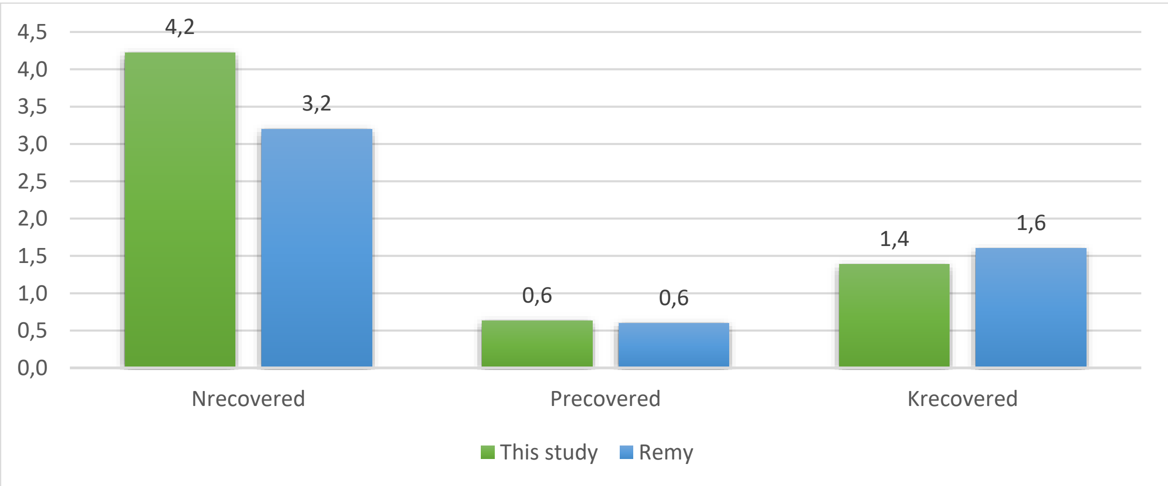


Figure A. 8 Validation of nutrient recovery

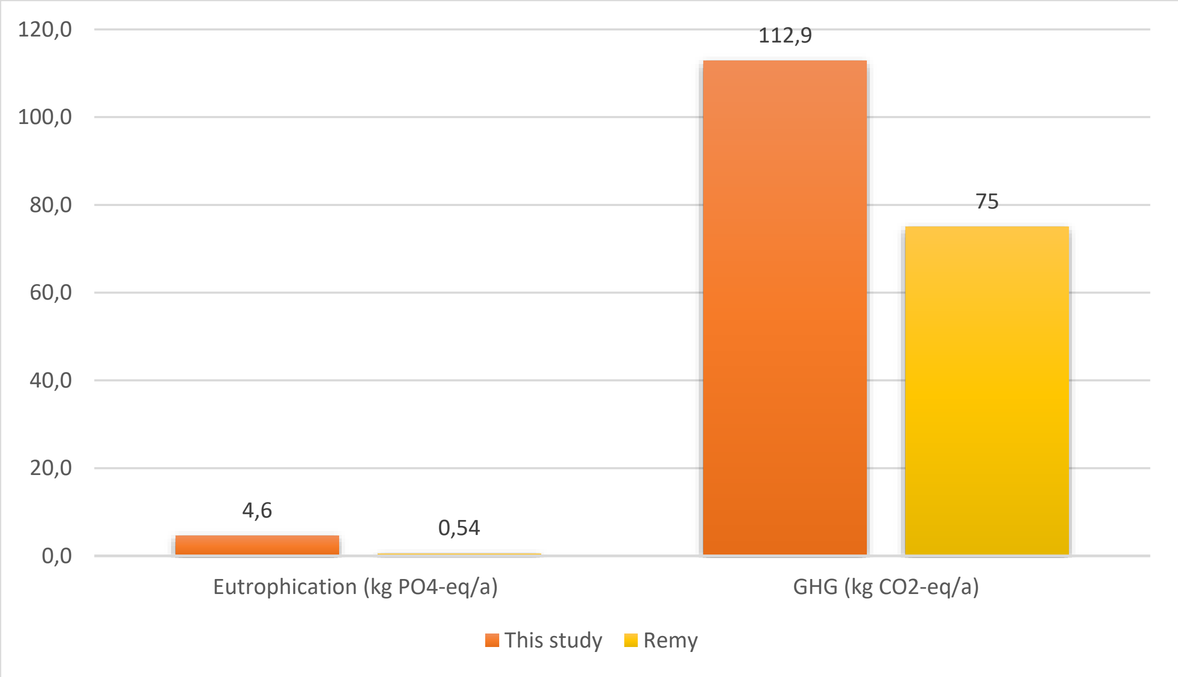


Figure A. 9 Validation of GHG and eutrophication

A.14 Visualization of mass and nutrient flow in Reference scenario (R0)

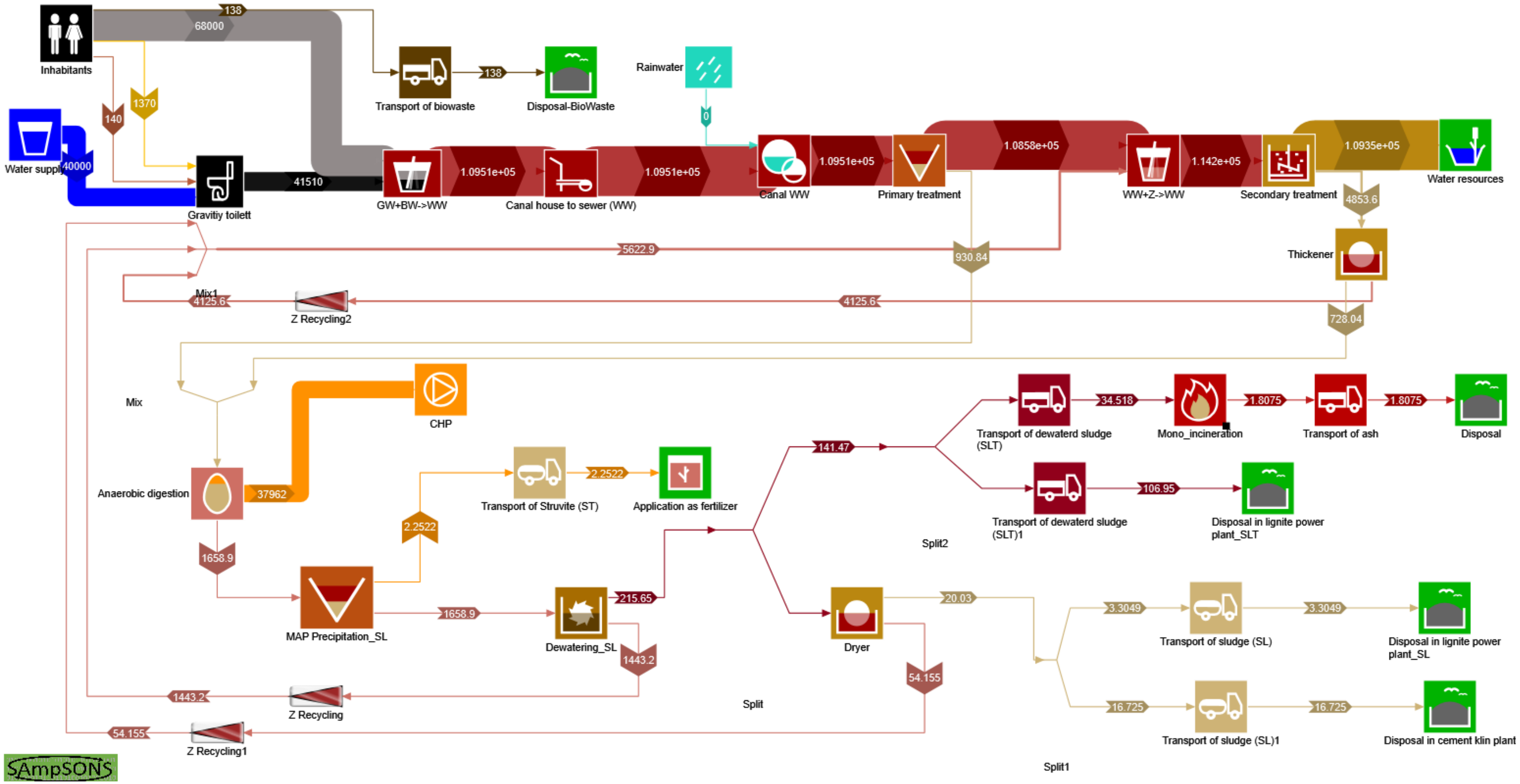


Figure A. 10 Visualization of flow in scenario R0 (m³/day)

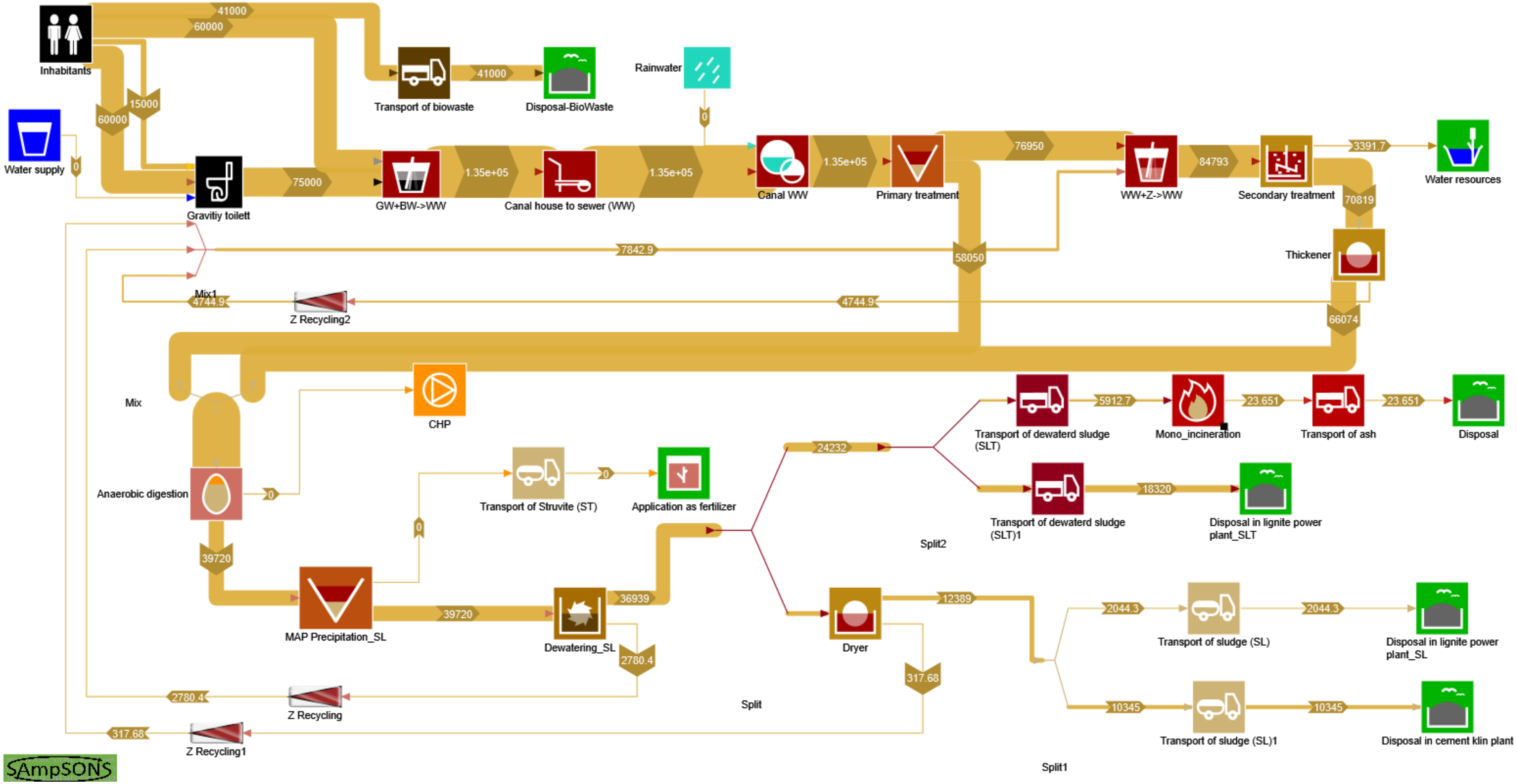


Figure A. 11 Visualization of COD load in Scenario R0 (kg/day)

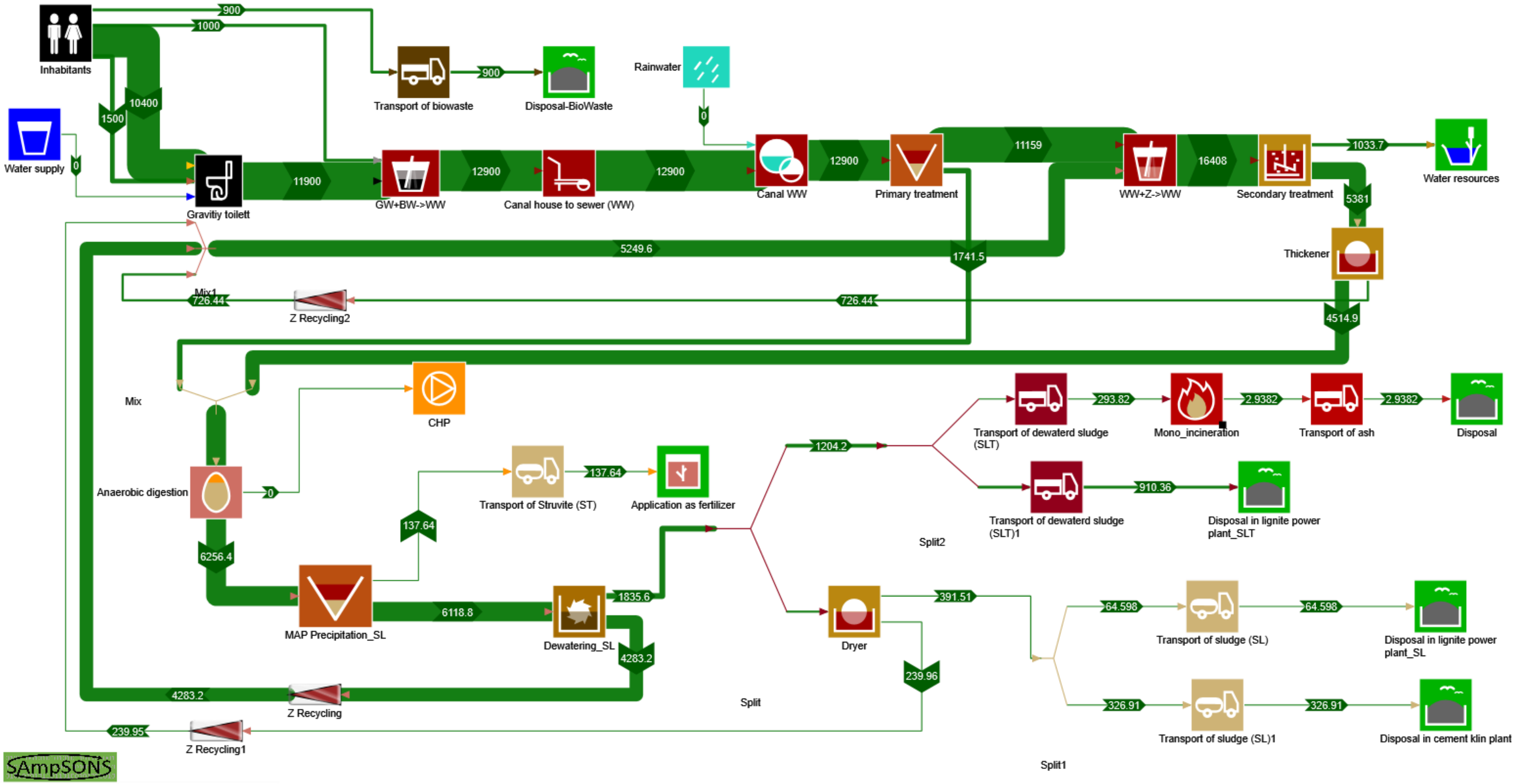


Figure A. 12 Visualization of N_{total} load in Scenario R0 (kg/day)

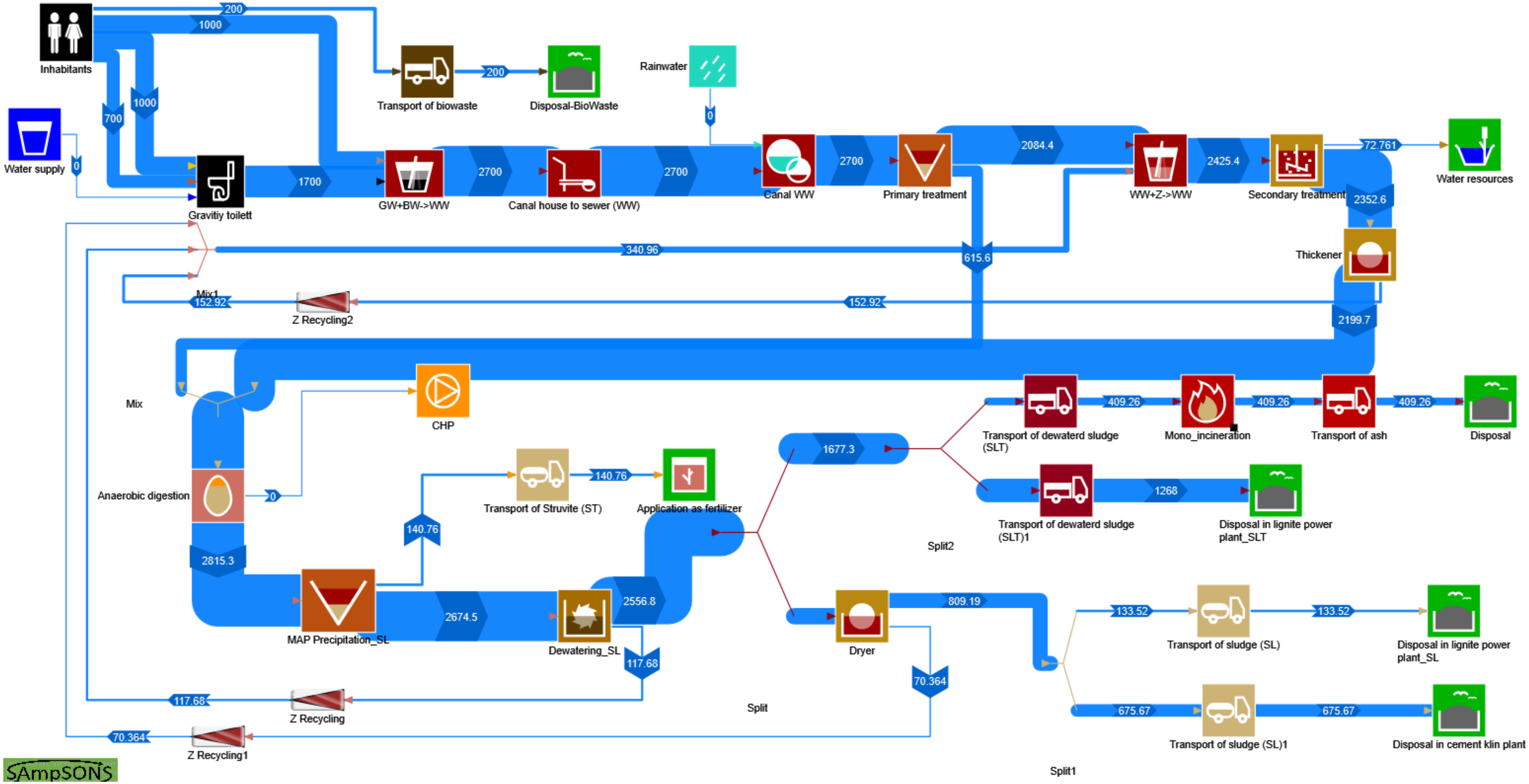


Figure A. 13 Visualization of P_{total} load in Scenario R0 (kg/day)

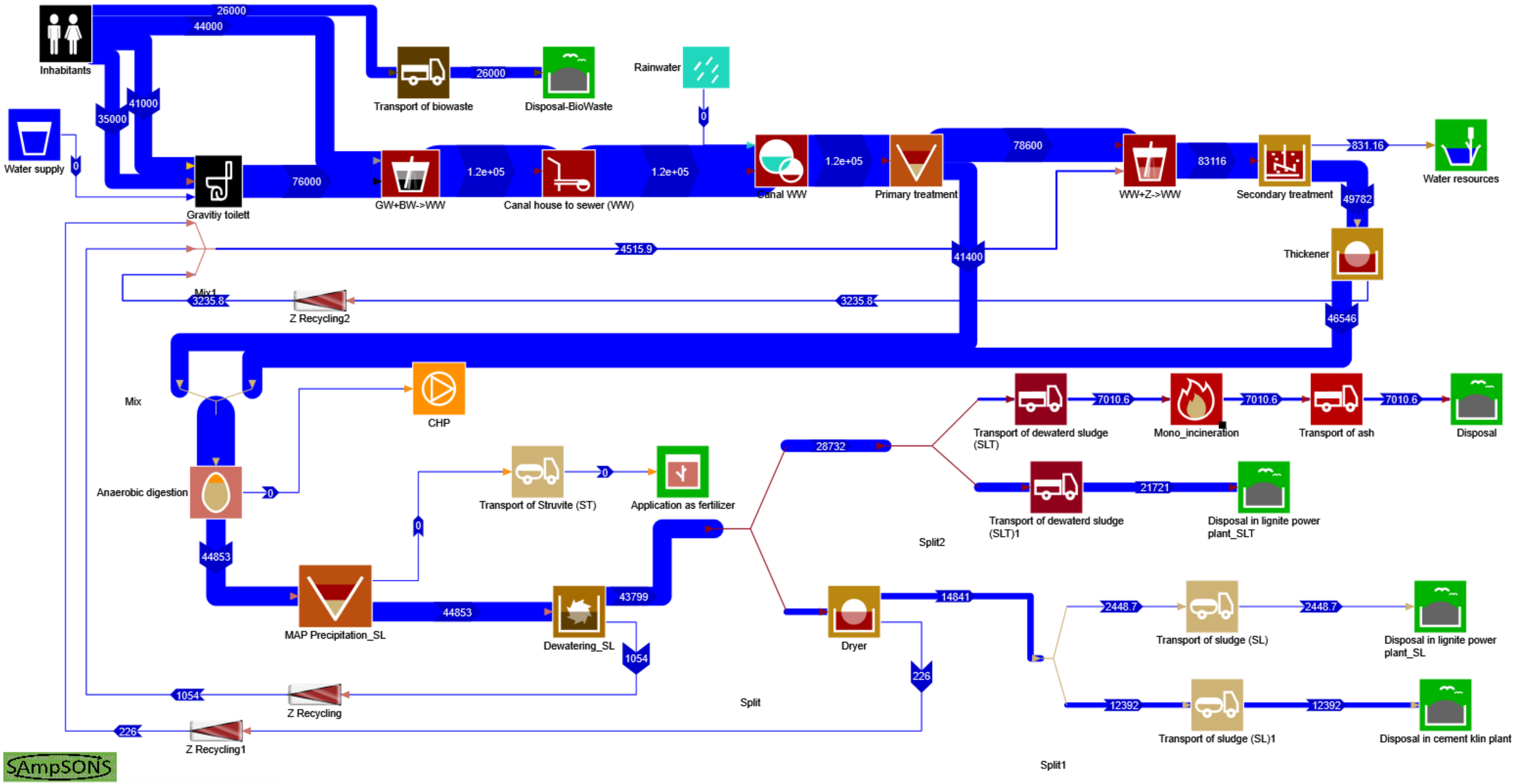


Figure A. 14 Visualization of DM load in Scenario R0 (kg/day)

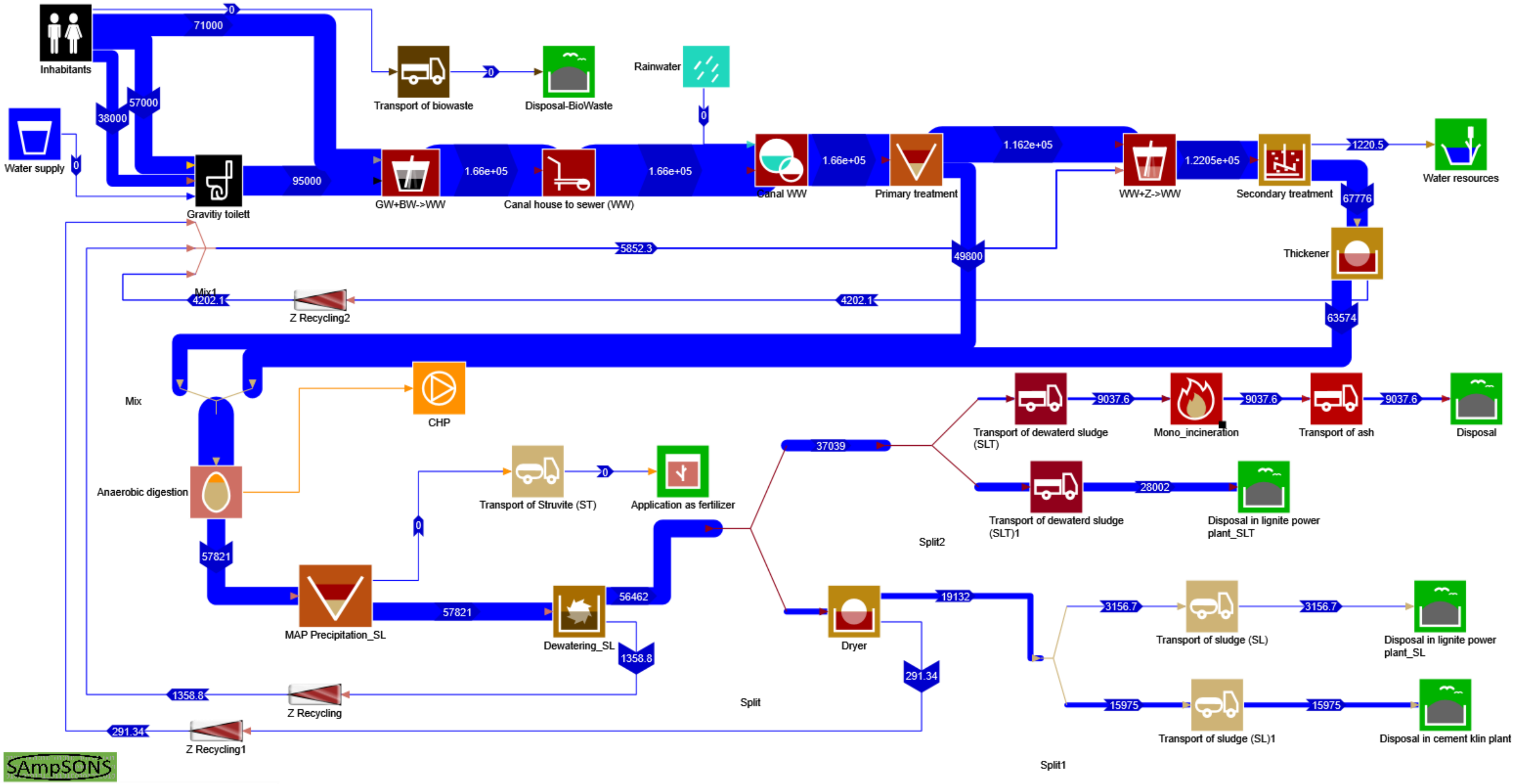


Figure A. 15 Visualization of oDM load in Scenario R0 (kg/day)

References

AbfKlärV (2017): Verordnung zur Neuordnung der Klärschlammverwertung. In: Bundesministerium für Umwelt, Bonn. Online verfügbar unter https://www.lanuv.nrw.de/fileadmin/lanuv/abfall/untersuchungsstellen/Neue_AbfKlserV_27_09_17.pdf.

AbwV (2018): Abwasserverordnung. Anhang 1 zur AbwV - Häusliches und kommunales Abwasser (4). Online verfügbar unter https://www.umwelt-online.de/recht/wasser/abw_vo/an1.htm.

Adam, C.; Peplinski, B.; Michaelis, M.; Kley, G.; Simon, F-G (2009): Thermochemical treatment of sewage sludge ashes for phosphorus recovery. In: Waste management (New York, N.Y.) 29 (3), S. 1122–1128. DOI: 10.1016/j.wasman.2008.09.011.

Ahn, Joon Ho; Kim, Sungpyo; Park, Hongkeun; Rahm, Brian; Pagilla, Krishna; Chandran, Kartik (2010): N2O emissions from activated sludge processes, 2008-2009: results of a national monitoring survey in the United States. In: Environmental science & technology 44 (12), S. 4505–4511. DOI: 10.1021/es903845y.

Al Baz, Ismail; Otterpohl, Ralf; Wendland, Claudia (Hg.) (2008): Efficient management of wastewater. Its treatment and reuse in the Mediterranean countries. Berlin, [London]: Springer.

Andersson, Kim; Dickin, Sarah; Rosemarin, Arno (2016): Towards “Sustainable” Sanitation: Challenges and Opportunities in Urban Areas. In: Sustainability 8 (12), S. 1289. DOI: 10.3390/su8121289.

Antonini, Samantha (2013): Nutrient recovery from human urine: Treatment options and reuse potential. Doktor der Agrarwissenschaften. Rheinischen Friedrich-Wilhelms-Universität Bonn.

ATV-DVWK-M 379, (2004): Merkblatt ATV-DVWK-M 379, Klärschlammtrocknung Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall Merkblatt 379.

Augustin, Kim; Skambraks, Anne-Katrin; Li, Zhiqiang; Giese, Thomas; Rakelmann, Ulf; Meinzinger, Franziska et al. (2014): Towards sustainable sanitation – the HAMBURG WATER Cycle in the settlement Jenfelder Au. In: Water Science and Technology: Water Supply 14 (1), S. 13–21. DOI: 10.2166/ws.2013.158.

Bach, Vanessa (2017): Assessment of abiotic and biotic resource use for products and regions in the context of sustainable development.

Bachmann, Nathalie (2015): Sustainable biogas production in municipal wastewater treatment plants. Anaerobic digestion. Unter Mitarbeit von IEA Bioenergy: IEA Bioenergy.

Balkema, Annelies J.; Preisig, Heinz A.; Otterpohl, Ralf; Lambert, Fred J.D (2002): Indicators for the sustainability assessment of wastewater treatment systems. In: Urban Water 4 (2), S. 153–161. DOI: 10.1016/S1462-0758(02)00014-6.

Balkema, Annelise J. van der Vleuten (2003): Sustainable wastewater treatment. Developing a methodology and selecting promising systems. PhD. Eindhoven, Techn. Univ, Eindhoven.

Barjenbruch, Matthias (2012): Wastewater disposal in rural areas. In: Desalination and Water Treatment 39 (1-3), S. 291–295. DOI: 10.1080/19443994.2012.669230.

Baumgartner, T.; Parravicini, V. (2018): Nitrogen management in side stream. D 4.4: Decision support for finding the appropriate resource and energy optimized SDE treatment technology.

BDEW (2019): Wasserstatistik. BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. Online verfügbar unter www.bdew.de.

Beier, M.; Sander, M.; Schneider, Y.; Rosenwinkel, K. (2008): Energieeffiziente Stickstoffelimination - Verfahrensüberblick zur Nitratation/Deammonifikation und Auswirkungen auf den Energiebedarf von Kläranlagen. (Energy-efficient Nitrogen

Removal: An Overview of Nitratation/Deammonification Processes and their Impact on the Energy Consumption of Wastewater Treatment Plants. In: KA - Korrespondenz Abwasser, Abfall 6, 2008, S. 671–678.

Benetto, Enrico; Nguyen, Diep; Lohmann, Torben; Schmitt, Bianca; Schosseler, Paul (2009): Life cycle assessment of ecological sanitation system for small-scale wastewater treatment. In: The Science of the total environment 407 (5), S. 1506–1516. DOI: 10.1016/j.scitotenv.2008.11.016.

Bisinella de Faria, A. B.; Spérandio, M.; Ahmadi, A.; Tiruta-Barna, L. (2015): Evaluation of new alternatives in wastewater treatment plants based on dynamic modelling and life cycle assessment (DM-LCA). In: Water research 84, S. 99–111. DOI: 10.1016/j.watres.2015.06.048.

Böcker, K; Eder, B; Kopp, J; Kopplow, O.; Müller, J.; Neis, U. et al. (2005): Wirtschaftlicher und betrieblicher Vergleich verschiedener Verfahren zur Klärschlammdesintegration, 2005, S. 189–196. Online verfügbar unter https://publikationen.bibliothek.kit.edu/1000005921.

Boehler, M.; Hernandez, A.; Fleiner, J.; Gruber, W.; Seyfried, A. (2018): WP4 – Nitrogen management in side stream. D-4.3:Operation and optimization of membrane ammonia stripping-Powerstep. Hg. v. Eawag.

Brunner, Paul H.; Rechberger, Helmut (2002): Anthropogenic Metabolism and Environmental Legacies. In Encyclopedia of global environmental change. Volume 3, Causes and consequences of global environmental change. Online verfügbar unter https://pdfs.semanticscholar.org/b027/689951e76e966ad110ee33b7233adf7895eb.pdf.

Buchert, L.; Deilmann, M.; Fritsche, U.; Jenseit, W.; Lipkow, A.; Rausch, C. et al. (2004): Nachhaltiges Bauen und Wohnen in Deutschland (Sustainable Construction and Housing in Germany. In German). Umweltbundesamtes. Berlin, Germany.

Burgada Ruiz, Alberto (2016): VACUUM SYSTEMS FOR ORGANIC WASTE IN BUILDINGS AND PRECINCTS. Faculty of Engineering and Information Technology, University of Technology, Sydney. Online verfügbar unter https://www.google.de/search?q=energy+demand+of+vacuum+toilet&rlz=1C1FGUR_enDE812DE812&oq=energy+demand+of+vacuum+toilet+&aqs=chrome.69i57.14487j0j8&sourceid=chrome&ie=UTF-8, zuletzt geprüft am 12.10.2018.

Campos, L. C. (2013): Modelling the Next Generation of Sanitation Systems. NewSan Prototype Simulator. Online verfügbar unter https://www.susana.org/en/knowledge-hub/resources-and-publications/library/details/1797.

Castillo, A.; Cheali, P.; Gómez, V.; Comas, J.; Poch, M.; Sin, G. (2016): An integrated knowledge-based and optimization tool for the sustainable selection of wastewater treatment process concepts. In: Environmental Modelling & Software 84, S. 177–192.

Chong, Meng Nan; Sharma, Ashok K.; Burn, Stewart; Saint, Christopher P. (2012): Feasibility study on the application of advanced oxidation technologies for decentralised wastewater treatment. In: Journal of Cleaner Production 35, S. 230–238. DOI: 10.1016/j.jclepro.2012.06.003.

CML 2001: GaBi Software. Online verfügbar unter http://www.gabi-software.com/support/gabi/gabi-lcia-documentation/cml-2001/.

Cossio, Claudia; McConville, Jennifer R.; Mattsson, Ann; Mercado, Alvaro; Norrman, Jenny (2020a): EVAS - a practical tool to assess the sustainability of small wastewater treatment systems in low and lower-middle-income countries. In: The Science of the total environment 746, S. 140938. DOI: 10.1016/j.scitotenv.2020.140938.

Cossio, Claudia; Norrman, Jenny; McConville, Jennifer; Mercado, Alvaro; Rauch, Sebastien (2020b): Indicators for sustainability assessment of small-scale wastewater treatment plants in low and lower-middle income countries. In: Environmental and Sustainability Indicators 6, S. 100028. DOI: 10.1016/j.indic.2020.100028.

Cote, Mauricio (2016): Circularity of carbon-based material systems in the German anthroposphere. Technische Universität Darmstadt; Institut IWAR, Darmstadt.
Curran, M. A. (2007): Co-Product and Input Allocation Approaches for Creating Life Cycle Inventory Data: A Literature Review 12 (Special Issue 1).
2015: DIN - VDI 4600 BLATT 1 - Cumulative energy demand - Examples | Engineering360. Online verfügbar unter https://standards.globalspec.com/std/9952262/vdi-4600-blatt-1, zuletzt geprüft am 30.05.2020.
Dockhorn, T. (2006): Ressourcenökonomische Anreize für ein zukunftsfähiges Stoffstrommanagement in der kommunalen Abwasserwirtschaft. Institut für SiedlungswasserwirtschaftTechnische Universität Braunschweig. Kommunale Abwasserbehandlung. In: Nr. 1 53 (Kommunale AbwasserbehandlungKA – Abwasser, Abfall).
Dockhorn, T. (2007a): Stoffstrommanagement und Ressourcenökonomie in der kommunalen Abwasserwirtschaft: Ges. zur Förderung des Inst. für Siedlungswasserwirtschaft an der Techn. Univ. Braunschweig (Veröffentlichung des Institutes für Siedlungswasserwirtschaft der Technischen Universität Braunschweig).
Dockhorn, Thomas (2007b): Stoffstrommanagement und Ressourcenökonomie in der kommunalen Abwasserwirtschaft. Heft 74. Braunschweig, Germany.: Institutes Siedlungswasserwirtschaft.
Dodd, Michael C.; Zuleeg, Steffen; Gunten, Urs von; Pronk, Wouter (2008): Ozonation of source-separated urine for resource recovery and waste minimization: process modeling, reaction chemistry, and operational considerations. In: Environmental science & technology 42 (24), S. 9329–9337. DOI: 10.1021/es800560r.
DüV (2017): Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen, vom Bundesministerium für Ernährung und Landwirtschaft.
DVGW (2011): Information Wasser Nr. 77 zu Energieeffizienz. Hg. v. Michael Plath und Knut Wichmann.
DWA (Hg.) (2008): Aufbereitungsstufen für die Wasserwiederverwendung. DWA Themen. Hennef: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.,
DWA (Hg.) (2009): Treatment steps for water reuse. Hennef: Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.,
DWA-Arbeitsgruppe KA-1.6 (2017): Neuartige Sanitärsystem (NASS). Eine Bilanzierung von Nährstoffen, Energieverbrauch und CO2-emission, Arbeitsbericht der DWA-Arbeitsgruppe KA-1.6 „Bemessungshinweise“ im Fachausschuss KA-1 „Neuartige Sanitärsysteme“, zuletzt geprüft am 18.10.2018.
DWA-Neuartige Sanitärsysteme (2015): Neuartige Sanitärsysteme Begriffe, Stoffströme, Behandlung von Schwarz-, Braun-, Gelb-, Grau- und Regenwasser, Stoffliche Nutzung. Kromsdorf: Bauhaus-Universitätsverlag als Imprint von VDG Weimar. Online verfügbar unter www.dwa.de.
DWA-A 131, Juni 2016: DWA-Regelwerk-Arbeitsblatt DWA-A 131, Bemessung von einstufigen Belebungsanlagen.
DWA, December 2015: DWA-Regelwerk-Arbeitsblatt DWA-A 216, Energiecheck und Energieanalyse Instrumente zur Energieoptimierung von Abwasseranlagen.
ECETOC (1994): Ammonia Emissions to Air in Western Europe. European Centre of Ecotoxicology and Toxicology of Chemicals. TR-062. Brussels, Belgium. (ISSN:-0773-8072-62).
Ellis, K. V.; Tang, S. L. (1991): Wastewater Treatment Optimization Model for Developing World. I: Model Development. In: Journal of Environmental Engineering 117 (4), S. 501–518. DOI: 10.1061/(ASCE)0733-9372(1991)117:4(501).

Elmitwalli, Tarek A.; Otterpohl, Ralf (2007): Anaerobic biodegradability and treatment of grey water in upflow anaerobic sludge blanket (UASB) reactor. In: Water research 41 (6), S. 1379–1387. DOI: 10.1016/j.watres.2006.12.016.
ISO 14040, 2006: Environmental management, Life Cycle Assessment, Principles and framework.
Eriksson, Eva; Auffarth, Karina; Henze, Mogens; Ledin, Anna (2002): Characteristics of grey wastewater. In: Urban Water 4 (1), S. 85–104. DOI: 10.1016/S1462-0758(01)00064-4.
Escher, Beate I.; Pronk, Wouter; Suter, Marc J. F.; Maurer, Max (2006): Monitoring the removal efficiency of pharmaceuticals and hormones in different treatment processes of source-separated urine with bioassays. In: Environmental science & technology 40 (16), S. 5095–5101. DOI: 10.1021/es060598w.
Evers, Karl Wolfgang (2009): Wasser als Lebensmittel. Trinkwasser, Mineralwasser, Quellwasser, Tafelwasser. 1. Aufl. Hamburg: Behr.
Fewless, Kimberly LeMonde (2015): CONSIDERATIONS FOR IMPLEMENTING SOURCE SEPARATION AND TREATMENT OF URINE, GRAYWATER, AND BLACKWATER. Master thesis. Colorado State University, Fort Collins, Colorado. Department of Civil and Environmental Engineering.
Foley, Jeffrey; Haas, David de; Yuan, Zhiguo; Lant, Paul (2010): Nitrous oxide generation in full-scale biological nutrient removal wastewater treatment plants. In: Water research 44 (3), S. 831–844. DOI: 10.1016/j.watres.2009.10.033.
Friedler, E.; Hadari, M. (2006): Economic feasibility of on-site greywater reuse in multi-storey buildings. In: Desalination 190 (1-3), S. 221–234. DOI: 10.1016/j.desal.2005.10.007.
Ganrot, Zsófia (2005): Urine processing for efficient nutrient recovery and reuse in agriculture. Department of Environmental Science and Conservation, Göteborg University.
Gao, Han; Scherson, Yaniv D.; Wells, George F. (2014): Towards energy neutral wastewater treatment: methodology and state of the art. In: Environmental science. Processes & impacts 16 (6), S. 1223–1246. DOI: 10.1039/C4EM00069B.
Garrido-Baserba, M.; Hospido, A.; Reif, R.; Molinos-Senante, M.; Comas, J.; Poch, M. (2014): Including the environmental criteria when selecting a wastewater treatment plant. In: Environmental Modelling & Software 56, S. 74–82. DOI: 10.1016/j.envsoft.2013.11.008.
Garrote, L.; Tsakiris, G.; Tsihrintzis, V. A.; Vangelis, H.; Tigkas, D (Hg.) (2019): Managing Water Resources for a Sustainable Future. Proceedings of the 11th World Congress of EWRA on Water Resources and Environment. 11th WORLD CONGRESS on Water Resources and Environment. Madrid, Spain, 25-29 June.
Germer, Jörn (2009): Urine-diverting vacuum sanitation system - Beijing, China. Case study of SuSanA projects.
Gernaey, Krist V.; Jeppsson, U.; Vanrolleghem, Peter A.; Copp, John B. (2014): Benchmarking of Control Strategies for Wastewater Treatment Plants. London: IWA Publishing (Scientific and Technical Report Series, No. 23).
Godin, D.; Bouchard, C.; Vanrolleghem, P. A. (2012): Net environmental benefit: introducing a new LCA approach on wastewater treatment systems. In: Water Science & Technology 65 (9), S. 1624–1631. DOI: 10.2166/wst.2012.056.
Gößling-Reisemann, Stefan (2008): What Is Resource Consumption and How Can It Be Measured? In: Journal of Industrial Ecology 12 (1), S. 10–25. DOI: 10.1111/j.1530-9290.2008.00012.x.
Gros, Meritxell; Petrović, Mira; Ginebreda, Antoni; Barceló, Damià (2010): Removal of pharmaceuticals during wastewater treatment and environmental risk assessment using hazard indexes. In: Environment international 36 (1), S. 15–26. DOI: 10.1016/j.envint.2009.09.002.

Gross, Amit; Maimon, Adi; Alfiya, Yuval; Friedler, Eran (2015): Greywater Reuse.
Guest, Jeremy S.; Skerlos, Steven J.; Barnard, James L.; Beck, M. Bruce; Daigger, Glen T.; Hilger, Helene et al. (2009): A new planning and design paradigm to achieve sustainable resource recovery from wastewater. In: Environmental science & technology 43 (16), S. 6126–6130.
Halalsheh, M.; Dalahmeh, S.; Sayed, M.; Suleiman, W.; Shareef, M.; Mansour, M.; Safi, M. (2008): Grey water characteristics and treatment options for rural areas in Jordan. In: Bioresource technology 99 (14), S. 6635–6641. DOI: 10.1016/j.biortech.2007.12.029.
Hellström, Daniel; Jeppsson, Ulf; Kärrman, Erik (2000): A framework for systems analysis of sustainable urban water management. In: Environmental Impact Assessment Review 20 (3), S. 311–321. DOI: 10.1016/S0195-9255(00)00043-3.
Henze, M.; Gujer, W.; Mino, T.; van Loosedrecht, M. (2006): Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. In: Water Intelligence Online 5 (0), 9781780402369-9781780402369. DOI: 10.2166/9781780402369.
Henze, M.; Ledin, A. (2001): Types, characteristics and quantities of classic, combined domestic wastewaters.
Hernández Leal, L.; Temmink, H.; Zeeman, G.; Buisman, C.J.N. (2011): Characterization and anaerobic biodegradability of grey water. In: Desalination (270), S. 111–115. DOI: 10.1016/j.desal.2010.11.029.
Hernandez-Sancho, F.; Molinos-Senante, M.; Sala-Garrido, R. (2011): Cost modelling for wastewater treatment processes. In: Desalination 268 (1-3), S. 1–5. DOI: 10.1016/j.desal.2010.09.042.
Hoffmann, H.; Platzer, C.; Winker, M.; von Muench, E. (2011): Technology review of constructed wetlands. Subsurface flow constructed wetlands for greywater and domestic wastewater treatment. Hg. v. Dr. Elisabeth von Muench. Internationale Zusammenarbeit (GIZ) GmbH Sustainable sanitation - ecosan program. Eschborn, Germany, zuletzt geprüft am 17.11.2017.
Höglund, Caroline; Ashbolt, Nicholas; Stenström, Thor Axel; Svensson, Lennart (2002): Viral persistence in source-separated human urine. In: Advances in Environmental Research 6 (3), S. 265–275. DOI: 10.1016/S1093-0191(01)00057-0.
Horn, Jana von; Maurer, Max; Londong, Jörg; Lautenschläger, Sabine; Steinmetz, Heidrun; Hillenbrand, Thomas; Dockhorn, Thomas (2013): Welche neuartigen Sanitärsysteme (NASS) sind für Deutschland besonders Erfolg versprechend? In: KA: Korrespondenz Abwasser Abfall 60 (8), S. 673–683. DOI: 10.3242/kae2013.08.002.
Hügel, Katrin (2003): Ökobilanzen in der Siedlungswasserwirtschaft. Life Cycle Assessment in sanitary engineering. Ph.D. thesis. ETH, Zürich. Instituts für Hydromechanik und Wasserwirtschaft.
ifak technology + service GmbH: SIMBA#water | ifak. Version 03. Magdeburg, Germany: SIMBA#. Online verfügbar unter https://www.ifak.eu/en/products/simba-water, zuletzt geprüft am 26.09.2019.
ifak technology + service GmbH (2017): Visualisation and sustainability assessment of new and alternative sanitation systems | ifak Magdeburg. Björnsen Beratende Ingenieure (BCE), Koblenz (Konsortialführer); Technische Universität Berlin, Fachgebiet Siedlungswasserwirtschaft; Bauhaus-Universität Weimar - Bauhaus-Institut für zukunftsweisende Infrastruktursysteme (b.is); Institut für Automation und Kommunikation e. V. (ifak), Magdeburg. Magdeburg, Germany: ifak. Online verfügbar unter https://www.ifak.eu/en/products/sampsons, zuletzt geprüft am 26.09.2019.
IINAS (2019): Der nichterneuerbare kumulierte Energieverbrauch und THG- Emissionen des deutschen Strom- mix im Jahr 2018 sowie Ausblicke auf 2020 bis 2050. Online verfügbar unter http://iinas.org/tl_files/iinas/downloads/GEMIS/2019_KEV_THG_Strom-2018_2020-2050.pdf, zuletzt geprüft am 30.07.2020.

IPCC (2006): IPCC. Guidelines for National Greenhouse Gas Inventories,Emission of wastewater treatment and discharge.
Istenic, Darja; Bodik, Igor; Bulc, Tjasa (2015): Status of decentralised wastewater treatment systems and barriers for implementation of nature-based systems in central and eastern Europe. In: Environmental science and pollution research international 22 (17), S. 12879–12884. DOI: 10.1007/s11356-014-3747-1.
Jefferson, B. (Hg.) (2019): How will switching from water recycling to resource factories impact disinfection by product formation? 12th IWA International Conference on Water Reclamation and Reuse. Berlin, Germany, 16 June 20019. IWA.
Jeppsson, Ulf; Baky, A.; Hellström, D.; Jönsson, H.; Kärrman, E. (2005): The URWARE Wastewater Treatment Plant Models. 055-0225. Chalmers University of Technology,Gothenburg,Sweden.
Johansson, Mats (2000): Urine separation - closing the nutrient cycle,. Stockholm Water Company, Stockholm, Sweden. Stockholm. Online verfügbar unter https://www.google.de/search?q=Ganrot%2C+Z.+(2005)%3A+Urine+processing+for+efficient+nutrient+recovery+and+reuse+in+agriculture.+Department+of+Environmental+Science+and+Conservation%2C+G%C3%B6teborg+University&ie=utf-8&oe=utf-8&client=firefox-b&gfe_rd=cr&ei=admiWMWEE-ml8wfk5aqgDg#q=Urine+separation+-+closing+the+nutrient+cycle%2C+Stockholm., zuletzt geprüft am 14.02.2017.
Johansson, Mats; Jönsson, Hakan; Högland, Caroline; Richert Stintzing, Anna; Rodhe, Lena (2000): Source separated human urine. Closing the nutrient cycle. Unter Mitarbeit von VERNA Ecology. Hg. v. Mats Johansson. The Stockholm Water Company. Stockholm, Sweden.
Jönsson, H.; Baky, A.; Jeppsson,, U.; Hellström, D.; Kärrman, E. (2005): Composition of urine, faeces,greywater and biowaste for the utilization in URWARE model. Urban Water Report. CHALMERS UNIVERSITY OF TECHNOLOGY. Chalmers University of Technology,Gothenburg, Sweden.
Jönsson, Håkan; Stenström, Thor-Axel; Svensson, Jan; Sundin, Annika (1997): Source separated urine-nutrient and heavy metal content, water saving and faecal contamination. In: Water Science & Technology 35 (9), S. 145–152. DOI: 10.2166/wst.1997.0338.
Jorgensen, Andreas; Le Bocq, Agathe; Nazarkina, Liudmila; Hauschild, Michael (2008): Methodologies for social life cycle assessment. In: Int J Life Cycle Assessment 13 (2), S. 96–103. DOI: 10.1065/lca2007.11.367.
Kabbe, C. (2013): Sustainable sewage sludge management. Fostering phosphorus recovery. Unter Mitarbeit von Collaborative Project FP7. Berlin Centre of Competence for Water gGmbH. Online verfügbar unter http://www.p-rex.eu/, zuletzt geprüft am 09.09.2019.
Kampschreur, Marlies J.; van der Star, Wouter R. L.; Wielders, Hubert A.; Mulder, Jan Willem; Jetten, Mike S. M.; van Loosdrecht, Mark C. M. (2008): Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment. In: Water research 42 (3), S. 812–826. DOI: 10.1016/j.watres.2007.08.022.
Kloepffer, Walter (2008): Life cycle sustainability assessment of products. In: Int J Life Cycle Assessment 13 (2), S. 89–95. DOI: 10.1065/lca2008.02.376.
Kraus, Fabian; Zamzow, Malte; Conzelmann, Lea; Remy, Christian; Kleyböcker, Anne; Seis, Wolfgang et al. (2019): Ökobilanzieller Vergleich der P-Rückgewinnung aus dem Abwasserstrom mit der Düngemittel-produktion aus Rohphosphaten unter Einbeziehung von Umweltfolgeschäden und deren Vermeidung. Umweltbundesamt.
Kujawa-Roeleveld, K.; Fernandes, T.; Wiryawan, Y.; Tawfik, A.; Visser, M.; Zeeman, G. (2005): Performance of UASB septic tank for treatment of concentrated black water within DESAR concept. In: Water Science & Technology 52 (1-2), S. 307–313.

Kujawa-Roeleveld, Katarzyna; Zeeman, Grietje (2006): Anaerobic Treatment in Decentralised and Source-Separation-Based Sanitation Concepts. In: Rev Environ Sci Biotechnol 5 (1), S. 115–139. DOI: 10.1007/s11157-005-5789-9.

Kvarnström, E.; Bracken, P.; Ysunza, A.; Kärrman, E.; Finnson, A.; Saywell, D. (2004): Sustainability Criteria in Sanitation Planning. PEOPLE-CENTRED APPROACHES TO WATER AND ENVIRONMENTAL SANITATION.

Lamine, M.; Bousselmi, L.; Ghrabi, A. (2007): Biological treatment of grey water using sequencing batch reactor. In: Desalination 215 (1-3), S. 127–132. DOI: 10.1016/j.desal.2006.11.017.

Langergraber, Günter; Muellegger, Elke (2005): Ecological Sanitation--a way to solve global sanitation problems? In: Environment international 31 (3), S. 433–444. DOI: 10.1016/j.envint.2004.08.006.

Larrey-Lassalle, Pyrène; Catel, Laureline; Roux, Philippe; Rosenbaum, Ralph K.; Lopez-Ferber, Miguel; Junqua, Guillaume; Loiseau, Eléonore (2017): An innovative implementation of LCA within the EIA procedure: Lessons learned from two Wastewater Treatment Plant case studies. In: Environmental Impact Assessment Review 63, S. 95–106. DOI: 10.1016/j.eiar.2016.12.004.

Larsen, Tove A.; Alder, Alfredo C.; Eggen, Rik I. L.; Maurer, Max; Lienert, Judit (2009): Source separation: will we see a paradigm shift in wastewater handling? In: Environmental science & technology 43 (16), S. 6121–6125. DOI: 10.1021/es803001r.

Larsen, Tove A.; Gujer, Willi (1996): Separate management of anthropogenic nutrient solutions (human urine). In: Water Science & Technology 34 (3-4). DOI: 10.1016/0273-1223(96)00560-4.

Larsen, Tove A.; Udert, Kai M.; Lienert, Judit (2013): Source separation and decentralization for wastewater treatment. London: IWA.

Lema, Juan M.; Suárez, Sonia (2017): Innovative wastewater treatment & resource recovery technologies. Impacts on energy, economy and environment. London, UK: IWA Publishing.

LeMonde Fewless, Kimberly (2011): Source Separation and Treatment of Anthropogenic Urine (10).

Lendrum, Andrew Luc (2015): Sustainable wastewater treatment through innovative schemes involving autotrophic nitrogen removal. International Master of Science in Environmental Technology and Engineering. Ghent University, Belgium, zuletzt geprüft am 06.11.2017.

Lettinga, G.; Lier van, JB.; Zeeman, G. (2001): Sustainability in environmental protection, centralisation or decentralisation in Urban sanitation. the international symposium on low cost wastewater treatment and reuse. Cairo, Egypt, 2001.

Li, Fangyue; Wichmann, Knut; Otterpohl, Ralf (2009): Review of the technological approaches for grey water treatment and reuses. In: The Science of the total environment 407 (11), S. 3439–3449. DOI: 10.1016/j.scitotenv.2009.02.004.

Li, Zifu (2004): Grauwasserbehandlung und -wiederverwendung. Untersuchungen zur höherwertigen Wiederverwendung von Grauwasser in Verbindung mit teilstromorientierten ökologischen Sanitärkonzepten. PhD. Technische Universität Hamburg-Harburg, Hamburg. Abwasserwirtscahft und Gewässerschutz.

Liedtke, Christa; Bienge, Katrin; Wiesen, Klaus; Teubler, Jens; Greiff, Kathrin; Lettenmeier, Michael; Rohn, Holger (2014): Resource Use in the Production and Consumption System—The MIPS Approach. In: Resources 3 (3), S. 544–574. DOI: 10.3390/resources3030544.

Lienert, Judit; Larsen, Tove A. (2006): Considering user attitude in early Development of environmentally friendly technology: a case study of NoMix toilets. In: Environmental science & technology 40 (16), S. 4838–4844. DOI: 10.1021/es060075o.

Lienert, Judit; Larsen, Tove A. (2010): High acceptance of urine source separation in seven European countries: a review. In: Environmental science & technology 44 (2), S. 556–566. DOI: 10.1021/es9028765.
Lind, Bo-Bertil; Ban, Zsófia; Bydén, Stefan (2001): Volume reduction and concentration of nutrients in human urine. In: Ecological Engineering 16 (4), S. 561–566. DOI: 10.1016/S0925-8574(00)00107-5.
Lindner, Björn (2007): The black water loop. Water efficiency and nutrient recovery combined. PhD. Hamburg University of Technology (TUHH), Hamburg. Wastewater management and water protection.
Londong, J.; Hartmann, M. (2006): Belastungen der häuslichen Abwasserteilströme: Gegenüberstellung von Literaturwerten und gemessenen Werten und Auswirkungen auf die Anlagenplanung. Rheinisch-Westfälische, Gewässerschutz - Wasser - Abwasser (GWA). Unter Mitarbeit von 39. Essener Tagung für Wasser- und Abfallwirtschaft vom 29. – 31.03.2006. Hg. v. Pinnekamp J. (Hrsg.). Institut für Siedlungswasserwirtschaft,Technische Hochschule Aachen. Aachen (Bd. 202, S. 26/1 – 26/15.).
Londong, J.; Otterpohl, R. (2001): The Lambertsmühle Case: Ecologically and economically efficient decentralized wastewater and ressources management. 2nd IWA World Water Congress. Berlin, Germany, 2001.
Londong, Jörg; Maier, Kirsten (2016): Transitionswege im ländlichen Raum. Am Beispiel des Modellgebietes Wohlsborn-Rohrbach. Abschlussveranstaltung "Wasserinfrastruktur in der Stadt. Lünen,19. Mai 2016, 2016. Online verfügbar unter https://www.twistplusplus.de/twist-wAssets/docs/5_Londong_Maier_Transitionswege_im_laendlichen_Raum.pdf.
Lundin, Margareta (2002): Indicators for measuring the sustainability of urban water systems. A Life Cycle approach. CHALMERS UNIVERSITY OF TECHNOLOGY. Environmental Systems Analysis, zuletzt geprüft am 08.04.2019.
M.A.J. Huijbregts et al. (2016): A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization. ReCiPe 2016.
Makropoulos, C. K.; Natsis, K.; Liu, S.; Mittas, K.; d. Butler (2008): Decision support for sustainable option selection in integrated urban water management. In: Environmental Modelling & Software 23 (12), S. 1448–1460. DOI: 10.1016/j.envsoft.2008.04.010.
Maurer, M.; Pronk, W.; Larsen, T. A. (2006): Treatment processes for source-separated urine. In: Water research 40 (17), S. 3151–3166. DOI: 10.1016/j.watres.2006.07.012.
Meinzinger, F. (2010): Resource efficiency of urban sanitation systems : a comparative assessment using material and energy flow analysis. PhD. TUHH. Wastewater management and water protection.
Meinzinger, F.; Oldenburg, M. (2009): Characteristics of source-separated household wastewater flows. A statistical assessment. In: Water Science & Technology 59 (9), S. 1785. DOI: 10.2166/wst.2009.185.
Merz, Cornelia; Scheumann, René; El Hamouri, Bouchaib; Kraume, Matthias (2007): Membrane bioreactor technology for the treatment of greywater from a sports and leisure club. In: Desalination 215 (1-3), S. 37–43. DOI: 10.1016/j.desal.2006.10.026.
Montag, David; Everding, Wibke; Malms, Susanne; Pinnekamp, Johannes; Reinhardt, Joachim; Fehrenbach, Horst et al. (2015): Evaluating Concrete Steps for Advanced Phosphorus Recovery from Relevant Streams as well as for Efficient Phosphorus Utilization Summary. Environmental Research of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Project No. (FKZ) 3713 26 301).

Mrowiec, B.; Suschka, J. (2005): ANAEROBIC WASTEWATER TREATMENT PROCESS. Online verfügbar unter https://www.seed.abe.kth.se/polopoly_fs/1.650925!/JPSU16p13.pdf.
Muga, Helen E.; Mihelcic, James R. (2008): Sustainability of wastewater treatment technologies. In: Journal of environmental management 88 (3), S. 437–447. DOI: 10.1016/j.jenvman.2007.03.008.
Mujtaba, I. M.; Srinivasan, R.; Elbashir, N. O. (2017): The Water-Food-Energy Nexus: Processes, Technologies, and Challenges: CRC Press. Online verfügbar unter https://books.google.de/books?id=fvA0DwAAQBAJ.
Munn, R. E.; Timmerman, Peter (2002): Social and economic dimensions of global environmental change. Chichester: Wiley (Encyclopedia of global environmental change, v. 5).
Muñoz, Ivan; Milà i Canals,, Llorenç; Clift, Roland; Doka, Gabor (2007): A simple model to include human excretion and wastewater treatment in Life Cycle Assessment of food products. CES Working Paper 01/07. Centre for Environmental Strategy, University of Surrey,United Kingdom. Online verfügbar unter http://www.surrey.ac.uk/CES.
Nakamura, Shinichiro; Nakajima, Kenichi; Kondo, Yasushi; Nagasaka, Tetsuya (2007): The Waste Input-Output Approach to Materials Flow Analysis. In: Journal of Industrial Ecology 11 (4), S. 50–63. DOI: 10.1162/jiec.2007.1290.
Nolde, Erwin (2000): Greywater reuse systems for toilet flushing in multi-storey buildings – over ten years experience in Berlin. In: Urban Water 1 (4), S. 275–284. DOI: 10.1016/S1462-0758(00)00023-6.
Norström, A.; Erlandsson, A.; Kärrman, E. (2008): Environmental assessment and cost estimation of drinking water and wastewater systems for transition areas in Sweden. In: Water Science & Technology 57 (12), S. 2039–2042. DOI: 10.2166/wst.2008.315.
Oldenburg, Martin (2007): Final cost calculation report for the demonstration project “Sanitation Concepts for Separate Treatment of Urine, Faeces and Greywater “ (SCST). OtterWasser GmbH. Lübeck. Online verfügbar unter http://www.susana.org/en/resources/library/details/593.
Olsson, P.; Pellicer, C. (2018): Design and performance of advanced primary treatment-microscreen. d1-2-.
Ortiz, M.; Raluy, R. G.; Serra, L. (2007): Life cycle assessment of water treatment technologies. Wastewater and water-reuse in a small town. In: Desalination 204 (1-3), S. 121–131. DOI: 10.1016/j.desal.2006.04.026.
Otterpohl, R.; Braun, U.; Oldenburg, M. (2004): Innovative technologies for decentralised water-, wastewater and biowaste management in urban and peri-urban areas. In: Water Sci Technol 48 (11-12), S. 23–32.
Otterpohl, R.; Grottker, M.; Lange, J. (1997): Sustainable water and waste management in urban areas. In: Water Science & Technology 35 (9). DOI: 10.1016/S0273-1223(97)00190-X.
Otter-wasser (2009): Ecological housing estate, Flintenbreite, Lübeck, Germany. Case study of sustainable sanitation projects.
Palme, Ulrika; Lundin, Margareta; Tillman, Anne-Marie; Molander, Sverker (2005): Sustainable development indicators for wastewater systems – researchers and indicator users in a co-operative case study. In: Resources, Conservation and Recycling 43 (3), S. 293–311. DOI: 10.1016/j.resconrec.2004.06.006.
Patyk, Andreas; Reinhardt, Guido A. (1999): Düngemittel — Energie- und Stoffstrombilanzen. Braunschweig/Wiesbaden, Germany: Vieweg Verlag.
Paulo, P. L.; Begosso, L.; Pansonato, N.; Shrestha, Roshan R.; Boncz, M. A. (2009): Design and configuration criteria for wetland systems treating greywater. In: Water science and

technology : a journal of the International Association on Water Pollution Research 60 (8), S. 2001–2007. DOI: 10.2166/wst.2009.542.
Peter-Fröhlich, A.; Bonhmme, A.; Oldenburg, M. (2007): Sanitation Concepts for Separate Treatment of Urine, Faeces and Greywater (SCST) – Results. Annex 7.4 Project description and results PF 3.7.2007. Unter Mitarbeit von Berliner Wasserbetriebe. co-financed in the framework of the LIFE programme of the European Commission (LIFE03 ENV/D/000025). Online verfügbar unter www.kompetenz-wasser.de.
Popovic, Tamara; Kraslawski, Andrzej (2018): Quantitative Indicators of Social Sustainability and Determination of Their Interdependencies. Example Analysis for a Wastewater Treatment Plant. In: Period. Polytech. Chem. Eng. 62 (2), S. 224. DOI: 10.3311/PPch.10526.
Randall, D. G.; v. Naidoo (2018): Urine: The liquid gold of wastewater. In: Journal of Environmental Chemical Engineering 6 (2), S. 2627–2635. DOI: 10.1016/j.jece.2018.04.012.
Rebitzer, Gerald; Hunkeler, David; Jolliet, Olivier (2003): LCC-The economic pillar of sustainability: Methodology and application to wastewater treatment. In: Environ. Prog. 22 (4), S. 241–249. DOI: 10.1002/ep.670220412.
Remy, C. (2010): Life Cycle Assessment of conventional and source-separation systems for urban wastewater manageme. Ph.D. thesis, TU Berlin.
Remy, C. (2012a): LCA study of sludge treatment line in WWTP Berlin-Waßmannsdorf. CoDiGreen_LCA_Berlin_final. Kompetenzzentrum Wasser Berlin gGmbH. Berlin.
Remy, C. (2015): Sustainable sewage sludge management fostering phosphorus recovery and energy efficiency. Environmental_Impact_Assessment_LCA_Remy_2015.
Remy, C.; Jekel, M. (2008): Sustainable wastewater management: life cycle assessment of conventional and source-separating urban sanitation systems. In: Water science and technology : a journal of the International Association on Water Pollution Research 58 (8), S. 1555–1562. DOI: 10.2166/wst.2008.533.
Remy, C.; Ruhland, A. (2006): Ecological assessment of alternative sanitation Concepts with Life Cycle Assessment. Final report for subtask 5 of the demonstration project “Sanitation Concepts for Separate Treatment of Urine, Faeces and Greywater “ (SCST). Unter Mitarbeit von Technische Universität Berlin Institute of Environmental Technology Department of Water Quality Control. Kompetenzzentrum Wasser Berlin gGmbH, the European Commission (LIFE 03ENV/D/000025).
Remy, Christian (2012b): CoDiGreen_LCA_Braunschweig_final. Online verfügbar unter https://www.kompetenz-wasser.de/wp-content/uploads/2017/05/codigreen_lca_braunschweig_final.pdf.
Ronteltap, Mariska; Maurer, Max; Gujera Willi (2007): The behaviour of pharmaceuticals and heavy metals during struvite precipitation in urine - ScienceDirect. Online verfügbar unter http://www.sciencedirect.com/science/article/pii/S004313540700053X, zuletzt geprüft am 14.11.2017.
Rose, C.; Parker, A.; Jefferson, B.; Cartmell, E. (2015): The Characterization of Feces and Urine: A Review of the Literature to Inform Advanced Treatment Technology (17).
Rosemarin, Arno (2008): Pathways for sustainable sanitation. Achieving the millennium development goals. London, UK, New York: IWA Publishing, zuletzt geprüft am 15.02.2018.
Roskosch, A.; Heidecke, P. (2018): Klärschlamm-entsorgung in der Bundesrepublik Deutschland. Umweltbundesamt. Online verfügbar unter https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/2018_10_08_uba_fb_klaerschlamm_bf_low.pdf.

Sartorius, Christian; Hillenbrand, Thomas; Levai, Peter; Nyga, Ilka; Schulwitz, Martin; Tettenborn, Felix (2016): Indikatoren zur Bewertung alternativer Wasserinfrastrukturen im Projekt TWIST++. Projekt TWIST ++(Transitionswege WasserInfraSTruktursysteme).
Schaffner, Monika (2007): Applying a Material Flow Analysis Model to Assess River Water Pollution and Mitigation Potentials. Ph.D. Inauguraldissertation der Philosophisch-naturwissenschaftlichen Fakultät, der Universität Bern.
Schmidt, Sonja; Pahl-Wostl, Claudia (2007): Modeling Biowaste Flows for Life-Cycle Assessment: Calculation of the Potential and Collected Weight of Kitchen and Garden Waste - Schmidt - 2007 - Journal of Industrial Ecology - Wiley Online Library.
Schönberg, A.; Raupenstrauch, H.; Ponak, C. (2018): Recovery of Phosphorus in Sewage Sludge Treatment. Universal Medien GmbH, Munich.
Schoumans, Oscar F.; Bouraoui, Fayçal; Kabbe, Christian; Oenema, Oene; van Dijk, Kimo C. (2015): Phosphorus management in Europe in a changing world. In: Ambio 44 Suppl 2, S180-92. DOI: 10.1007/s13280-014-0613-9.
Schubert, Rabea-Luisa (2018): d2-1-advanced-control-strategy-for-nitrogen-removal-final. PowerStep.EU.
Schüch, A; Morscheck, G; Lemke, A; Nelles, M (2016): Bio-Waste Recycling in Germany – Further Challenges (35), S. 308–318. DOI: 10.1016/j.proenv.2016.07.011.
Schulz, C.; Rapp, T.; Conrad, A.; Hünken, A.; Seiffert, I.; Becker, K. et al. (2003): Trinkwasser: Elementgehalte im häuslichen Trinkwasser aus Haushalten mit Kindern in Deutschland. (Drinking water: elemental composition of drinking water in households with children). Umweltbundesamt. Dessau, Germany.
Sievers, Jan Christian (2018): Charakterisierung von Grauwasser. PhD. Bauhaus-Universität Weimar, Weimar.
Sikosana, Melissa K.L.N.; Randall, Dyllon G.; Blottnitz, Harro von (2017): A technological and economic exploration of phosphate recovery from centralised sewage treatment in a transitioning economy context. In: Water SA 43 (2), S. 343–353. DOI: 10.4314/wsa.v43i2.17.
Siracusa, G.; La Rosa, A. D. (2006): Design of a constructed wetland for wastewater treatment in a Sicilian town and environmental evaluation using the emergy analysis. In: Ecological Modelling 197 (3-4), S. 490–497. DOI: 10.1016/j.ecolmodel.2006.03.019.
Smith, Adam L.; Stadler, Lauren B.; Love, Nancy G.; Skerlos, Steven J.; Raskin, Lutgarde (2012): Perspectives on anaerobic membrane bioreactor treatment of domestic wastewater: a critical review. In: Bioresource technology 122, S. 149–159. DOI: 10.1016/j.biortech.2012.04.055.
Spuhler, D.; Scheidegger, A.; Maurer, M. (2018): Generation of sanitation system options for urban planning considering novel technologies. In: Water research 145, S. 259–278. DOI: 10.1016/j.watres.2018.08.021.
Spuhler, Dorothee; Germann, Verena; Kassa, Kinfe; Ketema, Atekelt Abebe; Sherpa, Anjali Manandhar; Sherpa, Mingma Gyalzen et al. (2020): Developing sanitation planning options: A tool for systematic consideration of novel technologies and systems. In: Journal of environmental management 271, S. 111004. DOI: 10.1016/j.jenvman.2020.111004.
Steinmetz, Heidrun; Meyer, Carsten; Reinhardt, Tobias (2013): Interkommunales Pilotprojekt zur Phosphorrückgewinnung aus Klärschlammaschen in Baden-Württemberg. Ministrium für Umwelt, Klima und Energiewirtschaft. Universität Stuttgart, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft.
SuSanA (2008): Towards more sustainable sanitation solutions: Sustainable Sanitation Alliance (SuSanA).
Tervahauta, Taina (2014): Phosphate and organic fertiliser recovery from black water. PhD. Wageningen University.

Tervahauta, Taina; Hoang, Trang; Hernández, Lucía; Zeeman, Grietje; Buisman, Cees (2013): Prospects of Source-Separation-Based Sanitation Concepts: A Model-Based Study. In: Water 5 (3), S. 1006–1035. DOI: 10.3390/w5031006.
Tervahauta, Taina; Rani, Sonia; Hernández Leal, Lucía; Buisman, Cees J. N.; Zeeman, Grietje (2014): Black water sludge reuse in agriculture: are heavy metals a problem? In: Journal of hazardous materials 274, S. 229–236. DOI: 10.1016/j.jhazmat.2014.04.018.
Tettenborn, F.; Behrendt, J.; Otterpohl, R. (2007): Resource recovery and removal of pharmaceutical residues Treatment of separate collected urine. Final report for task 7 of the demonstration project "Sanitation Concepts for Separate Treatment of Urine, Faeces and Greywater " (SCST). Unter Mitarbeit von Kompetenzzentrum Wasser Berlin gGmbH Berliner Wasserbetriebe. TUHH.
Tettenborn, Felix (2011): Aspects of systems for separate urine collection and treatment. Selected techniques and potential implementation in an urban context, Hamburg.
Thibodeau, Charles; Monette, Frédéric; Bulle, Cécile; Glaus, Mathias (2014): Comparison of black water source-separation and conventional sanitation systems using life cycle assessment. In: Journal of Cleaner Production 67, S. 45–57. DOI: 10.1016/j.jclepro.2013.12.012.
Tilley, E.; Ulrich, L.; Lüthi, C.; Reymond, P.; Schertenleib, R.; Zurbrügg, C. (2014): Compendium of Sanitation Systems and Technologies. Eawag and IWA. Dübendorf, Switzerland.
Trimmer, Caspar (2016): SanitationWastewater&Sustainability. FOREWORDMASKED_HR.pdf. Hg. v. Caspar Trimmer.
Tukker, Arnold; Jansen, Bart (2006): Environmental Impacts of Products: A Detailed Review of Studies. In: Journal of Industrial Ecology 10 (3), S. 159–182. DOI: 10.1162/jiec.2006.10.3.159.
UNEP (2009): Guidelines for Social Life Cycle Assessment of Products. United Nations Environment Programme. Paris, France, zuletzt geprüft am 24.09.2019.
United Nations (Hg.) (2018): Sustainable development goal 6. Synthesis Report on Water and Sanitation. New York: United Nations.
Verlicchi, P.; Al Aukidy, M.; Zambello, E. (2012): Occurrence of pharmaceutical compounds in urban wastewater. Removal, mass load and environmental risk after a secondary treatment--a review. In: The Science of the total environment 429, S. 123–155. DOI: 10.1016/j.scitotenv.2012.04.028.
Vogt, Regine (Hg.) (2002): Ökobilanz Bioabfallverwertung. Untersuchungen zur Umweltverträglichkeit von Systemen zur Verwertung von biologisch-organischen Abfällen. Berlin: Schmidt (Initiativen zum Umweltschutz, 52).
Wätzel, T.; Kraft, E. (2014a): Specified, anaerobic degradation of pharmaceuticals and digester gas recovery. EWA 17th International Symposium. Munich, Germany, 2014, zuletzt geprüft am 22.02.2019.
Wätzel, T.; Kraft, E. (2014b): Specified, anaerobic degradation of pharmaceuticals and digester gas recovery - A comprehensive study, zuletzt geprüft am 22.02.2019.
WCED (1987): Our Common Future, Chapter 2: Towards Sustainable Development. (The Brundtland Report). World Commission on Environment and Development,. Oxford, UK: Oxford University Press, zuletzt geprüft am 24.09.2019.
Wendland, C.; Deegener, S.; Behrendt, J.; Toshev, P.; Otterpohl, R. (2007): Anaerobic digestion of blackwater from vacuum toilets and kitchen refuse in a continuous stirred tank reactor (CSTR). In: Water Science & Technology 55 (7), S. 187–194. DOI: 10.2166/wst.2007.144.
Wiechmann, Benjamin; Dienemann, Claudia; Kabbe, Christian; Brandt, Simone; Vogel, Ines; Roskosch, Andrea (2013): Sewage sludge management in Germany. Umweltbundesamt (UBA). Dessau,Germany.

Wilderer, P. A. (2004): Applying sustainable water management concepts in rural and urban areas: some thoughts about reasons, means and needs. In: Water Science & Technology 49 (7), S. 8–16.

Wilsenach, J. A.; Maurer, M.; Larsen, T. A.; van Loosdrecht, M. C. M. (2003): From waste treatment to integrated resource management. In: Water Science & Technology 48 (1), S. 1–9.

Winker, Martina; Faika, Daniela; Gulyas, Holger; Otterpohl, Ralf (2008): A comparison of human pharmaceutical concentrations in raw municipal wastewater and yellowwater. In: The Science of the total environment 399 (1-3), S. 96–104. DOI: 10.1016/j.scitotenv.2008.03.027.

WRS (2001): Market survey_ Extremly low flush toilets. Plus urine diverting toilets and urinals, for collection of blackwater and /or urine. Water Revival Systems Uppsala AB. Sweden (SwedEnviro report NO2001:1).

Wu, Shubiao; Carvalho, Pedro N.; Muller, Jochen A.; Manoj, Valsa Remony; Dong, Renjie (2016): Sanitation in constructed wetlands: A review on the removal of human pathogens and fecal indicators. In: The Science of the total environment 541, S. 8–22. DOI: 10.1016/j.scitotenv.2015.09.047.

Zeeman, G.; Lettinga, G. (1999): The role of anaerobic digestion of domestic sewage in closing the water and nutrient cycle at community level. In: Water Science and Technology 39 (5). DOI: 10.1016/S0273-1223(99)00101-8.

Zeeman, Grietje; Kujawa, Katarzyna; Mes, Titia de; Hernandez, Lucia; Graaff, Marthe de; Abu-Ghunmi, Lina et al. (2008): Anaerobic treatment as a core technology for energy, nutrients and water recovery from source-separated domestic waste(water). In: Water science and technology : a journal of the International Association on Water Pollution Research 57 (8), S. 1207–1212. DOI: 10.2166/wst.2008.101.

Zeeman, Grietje; Kujawa-Roeleveld, Katarzyna (2011): Resource recovery from source separated domestic waste(water) streams; full scale results. In: Water Science & Technology 64 (10), S. 1987–1992. DOI: 10.2166/wst.2011.562.

Zhang, Lei (2016): Anaerobic treatment of municipal wastewater in a UASB-Digester system : temperature effect on system performance, hydrolysis and methanogenesis. Ph.D. Wageningen University, Wageningen, NL. Department of Environmental Technology.

Zhang, Zulin; Le Velly, Morgane; Rhind, Stewart M.; Kyle, Carol E.; Hough, Rupert L.; Duff, Elizabeth I.; McKenzie, Craig (2015): A study on temporal trends and estimates of fate of Bisphenol A in agricultural soils after sewage sludge amendment. In: The Science of the total environment 515-516, S. 1–11. DOI: 10.1016/j.scitotenv.2015.01.053.