Jovana Husemann

Development of a Decision Support Tool for Integrated Wastewater and Organic Material Flows Management in the Scope of Circular Economy

Stuttgarter Berichte zur Siedlungswasserwirtschaft Band 249

FORSCHUNGS- UND ENTWICKLUNGSINSTITUT FÜR
INDUSTRIE- UND SIEDLUNGSWASSERWIRTSCHAFT SOWIE
ABFALLWIRTSCHAFT E.V. (FEI)

Jovana Husemann

Development of a Decision Support Tool for Integrated Wastewater and Organic Material Flows Management in the Scope of Circular Economy

D 93

IMPRESSUM

Bibliographische Information der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet die Publikation in der Deutschen Nationalbibliographie; detaillierte bibliographische Daten sind im Internet über http://dnb.ddb.de abrufbar

Jovana Husemann
Development of a Decision Support Tool for Integrated Wastewater and Organic Material Flows Management in the Scope of Circular Economy

Forschungs- und Entwicklungsinstitut für Industrie- und Siedlungswasserwirtschaft
sowie Abfallwirtschaft e.V. (FEI)

Stuttgarter Berichte zur Siedlungswasserwirtschaft, Band 249

Layout:
Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft
der Universität Stuttgart ISWA
Bandtäle 2, 70569 Stuttgart

Druck:
e.kurz + co. druck und medientechnik gmbh
Kernerstr. 5, 70182 Stuttgart

Printed in Germany

Development of a Decision Support Tool for Integrated Wastewater and Organic Material Flows Management in the Scope of Circular Economy

Von der Fakultät für Bau- und Umweltingenieurwissenschaften der Universität Stuttgart zur Erlangung der Würde einer Doktor-Ingenieurin (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von
Jovana Husemann
Aus Krusevac

Hauptberichterin: Prof. Dr.-Ing. Heidrun Steinmetz
1. Mitberichter: Prof. Dr.-Ing. Martin Kranert
2. Mitberichter: Prof. Dr.-Ing. Renatus Widmann

Tag der mündlichen Prüfung: 23. April 2021

Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft
der Universität Stuttgart

2021

Acknowledgements

Conducting the International Doctoral Program “Environment Water” (ENWAT) at the University of Stuttgart was a highly rewarding and very challenging part of my life and could not have been accomplished without the support and assistance of many individuals and institutions.

The greatest acknowledgement goes to my supervisor Prof. Dr.-Ing. Heidrun Steinmetz for giving me the opportunity to conduct the doctoral studies under her generous supervision. I have learned a lot from her, not only in the field of wastewater management but as well as professional ethics. Her personal example was the strongest motivation for me during difficult times and my wish for further education and to pursuing a professional career in parallel to raising my children.

I am also thankful to my co-supervisors. To Prof. Dr.-Ing. Martin Kranert I would like to thank for his important insight in the area of municipal waste management, which certainly extended my thinking and influenced my overall professional career path. Prof. Dr.-Ing. Renatus Widmann thank you for the thesis revision.

I acknowledge gratefully the German Federal Ministry of Education and Research (BMBF) for providing me the IPSWaT-scholarship for the ENWAT doctoral studies. To the ENWAT Course Director Dr.-Ing. Gabriele Hartmann, I thank you the support concerning the formalities of the doctoral program and the scholarship. To Dragana Oberst I am grateful for support during the application process and to Roman Hemmer for his support and mentorship at the initial stage of the studies.

During the studies, generous support through diverse projects was also received through the State of Baden Württemberg and the Ministry of the Environment, Climate Protection and the Energy Sector as well as the State Ministry. Here I would like to thank Ms. Carmen Hawkins for her tremendous support. Finally, the municipality of Stara Pazova led by Mayor Mr. Djordje Radinovic financially sponsored the wastewater measurement campaign and I would like to thank them sincerely for that. I would like to thank Oswald-Schulze Stifftung for the financial support to participate in a doctoral course at the Technical University of Denmark in 2015 and the IWA 4th Eastern European Water Professional Conference in 2012 in St. Petersburg.

During the ENWAT doctoral studies I have had a great opportunity to professionally and personally develop myself in an international surrounding. To my dearest colleagues Clauadia, Asya, Dunja, Peace, Kristy, Caren, Mehari, Marie, Olga, Cristina, Carlos, Diego, Christian, Josif it was my greatest pleasure of having lunch breaks and spending my free time with you. Thank you for the countless moments of emotional and professional support.

My dearest friend Katja, as always you were there for me and I thank you for your encouragement and mental support. My friends Marta, Stephan, Achim and Alicia thank you for the relaxing evenings we spent in Stuttgart. My cousin Pedja I thank for the final proof reading of the Thesis.

My final and profound gratitude goes to my family, the members of the family Cosic and the family Husemann. To my mother, I would like to thank for believing in me and showing me that the sky is the limit. To my father, for showing me the importance of pursuing education and having a professional career through his own example. And to my darling sister for her critical review of the dissertation, the endless emotional support and having an ear for all my worries. I am deeply grateful to my parents- and sister-in-law for their very generous daily assistance and great support provided to my two children, especially during the COVID-19 pandemic.

To my husband Dr. Christoph Husemann and our dearest children Emilia and Philipp, I would like to express endless gratitude for your immense patience. This work is dedicated to you.

Journal Publications

A significant part of this dissertation has been published in the following publications:

1. Husemann, J.; Steinmetz, H.
   Case study Serbia: Nexus orientated wastewater management
   Watersolution 1/2016, 2016, **s.22ff.**, 77-87.

2. Pistocchi, A.; Husemann, J.; Masi, F.; Nanu, C.*(eds.)*
   Wastewater treatment in the Danube region: opportunities and challenges.
   EUR 30106 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-16429-6 (online),978-92-76-16428-9 (print), doi:10.2760/220413 (online),10.2760/16723 (print), JRC115606.

3. Ganora, D.; Hospido, A.; Husemann, J.; Krampe, J.; Loderer, C.; Longo, S.; Moragas Bouyat, L.; Obermaier, N.; Piraccini. E.; Satnev, S.; Váci, L.; Pistocchi, A.
   Opportunities to improve energy use in urban wastewater treatment: a European-scale analysis
   Environ. Res. Lett. 14 (2019) 044028, 2019*, https://doi.org/10.1088/1748-9326/ab0b54.*

Selected Conference Publications

Additionally, most of the work in this dissertation has also been presented at several international conferences and workshops and published in the respective conference proceedings:

4. <u>Husemann, J.</u>
   Wastewater is more than just Wastewater. The "Synthesis Centres" Approach
   Podium Presentation of the International Workshop on Water Management in the Danube River Basin Water Environment organized by ICPDR, World bank and IAWD, Bucharest, Romania, 28-29 November 2017.

5. Husemann, J.; Steinmetz, H.
   Cooperation among Danube Countries in Water Research and Management – Holistic Material Flow Management of Wastewater, Waste, Biomass and Energy in Stara Pazova and Indjija Basin
   Podium Presentation and Proceedings of the European Commission, Joint Research Centre – Scientific Support to the Danube Strategy – Water Workshop, Ulm, Germany, 27 November 2015.

6. Husemann, J.; Steinmetz, H.
   Technological Innovations for Collection, Treatment, and Re-Use of Water
   Podium Presentation of the First Preparatory Meeting of the 23rd OSCE Economic and Environmental Forum "Water Governance in the OSCE Area – Increasing Security and Stability through Co-Operation", Vienna, Austria, 26-27 January 2015.

7. Husemann, J.; Tanskovic, D.; Steinmetz, H.
   Does Serbia Need Own Design Guidelines for Wastewater Treatment Plant Design? Case Study "EastSrem"
   Podium Presentation and Proceedings of the IWA 7th Eastern European Young and Senior Water Professionals Conferences, Belgrade, Serbia, 17-19 September 2015.

8. Husemann, J.; Espinosa-Gutiérrez, T. Y. B.; Srinivasan, S.; Al Janabi, F. G.: Zhang, L.
   Towards Nexus Approach: Case Studies on Integrated Management of Water, Soil and Waste
   Proceedings of the International Kick-Off Workshop: Advancing a Nexus Approach to the Sustainable Management of Water, Soil and Waste, Dresden, Germany, 11-12 November 2013.

9. Husemann, J.; Steinmetz, H.
   Material Flow Management Based Approach for Achieving IWRM in Serbia: Example of the City of Cacak
   Podium Presentation and Proceedings of the IWA 4th Eastern European Young and Senior Water Professionals Conferences, Saint Petersburg, Russia, 04-06 September 2012.

Abstract

Efficient resource utilization, productivity gains and reducing waste flows are among the major aims of sustainable development. To reduce Europe’s dependency on conventional external material and energy flows, Europe is working to transit from a linear to a Circular Economy society. Circular Economy promotes reutilizing material and energy flows within defined system boundaries, aiming to reduce waste generation and disposal. While conventional wastewater treatment provides safe effluent discharge in line with the environmental standards and human health policy, it in part neglects resources efficiency. If we seek to minimize material and energy inputs and waste outputs, while increasing resource recovery and efficiency, it makes sense to rethink the conventional, single-sectorial management approach, and consider integrated management of sectors sharing a common material throughout.

Although recent research acknowledges the potential advantages of cross-sectoral management of resources, practical examples are still lacking. Thus, decision-makers are uninformed of the resource and energy potentials of - and lack practical recommendations on how - to better utilize their organic material flows such as sewage sludge, bio-waste and agricultural waste. Considering wastewater management as a central sector, this research examines the potential to integrating the management of “unwanted” organic material flows, originating specifically from solid waste management and agriculture sectors. The overall objective of this research was to develop a universal, user-friendly Decision Support Tool (DST) to assess the potential of applying integrated infrastructure projects.

The DST is an Excel-based tool that conducts mass and energy balances and economic analyses of integrated wastewater and organic material flows treatment scenarios, based on individual user inputs. The DST allows users to assess material and energy recovery and financial projections for sixteen possible treatment scenarios, defined by energy and nutrient recovery and water re-use application. Further, the DST allows users to evaluate two variants: either conventional, centralized wastewater and organic flows treatment or modular approach by incorporating decentralized wastewater treatment for rural communities and organic flows treatment. Based on user inputs, the DST graphically illustrates the results of two variants of a given scenario and quantifies phosphorus, energy and water re-use potentials, conducts a cost-benefit analysis, calculates the Net Present Value for both variants, and conducts a comparative assessment.

To test the DST, a Case Study Region (CSR) in Serbia was selected and the input data was collected and recorded from numerous sources from January 2013 through December 2014. Firstly, official data available from public institutions, statistics, municipal records and National Treasury of Serbia were collected and evaluated. Due to lacking and inconsistent data, a wastewater measurement campaign, and three surveys were conducted. The measurement campaign was conducted at a key point in the current sewer system, measuring wastewater flow rates and pollutants concentrations, leading to key findings to help defining wastewater flow and composition, infiltration and other conditions in the CSR. The three surveys included Industrial Wastewater Survey, Bio-Waste Survey and Agro-Waste Survey. Thus, additional outcomes of this research include the wastewater flows, pollutants loads and other key design parameters that can be used by the CSR and other municipalities going forward.

The research shows that integrated solutions like those examined herein demonstrate a positive impact on Circular Economy application at a local level. The DST's utility and practicality was tested on the Serbia CSR. Although applied only to the Serbia CSR, the developed DST is intended to be universally applicable under a broad range of local factors and conditions. The DST provides decision-makers with a tool to better understand the benefits of integrated resource management; quantify all available and/or potential organic waste flows; calculate energy and nutrient recovery potential; and perform preliminary cost and financial estimates. The DST is user-friendly and provides a schematic visualization of mass and energy balance results, providing users with a quick view of potentials.

In sum, this research provides a methodological approach for planning integrated management projects on a local level and offers a developed DST that can be used by many countries and municipalities that are planning future wastewater and environmental infrastructure projects. To better understand the applicability and limitations of the DST, future case studies can consider technical extensions of the tool to be applicable for other, new technologies; consider seasonal, cyclical and future changes in waste and wastewater flows and compositions.

Kurzfassung

Effiziente Ressourcennutzung, Produktivitätssteigerungen und die Reduzierung von Abfallströmen gehören zu den wichtigsten Zielen einer nachhaltigen Entwicklung. Damit die sich europäische Abhängigkeit von konventionellen externen Material- und Energieströmen verringert, strebt Europa einen Wandel von einer linearen zu einer Kreislaufwirtschaft an. Die Kreislaufwirtschaft fördert die Wiederverwendung von Material- und Energieströmen innerhalb definierter Systemgrenzen und bezweckt damit die Verringerung der Abfallerzeugung und -entsorgung. Die konventionelle Abwasserbehandlung sorgt zwar für eine sichere Abwasserableitung im Rahmen der Umwelt- und Gesundheitspolitik, vernachlässigt aber teilweise die Ressourceneffizienz. Um das Ziel einer Minimierung des Material- und Energieverbrauchs sowie der Abfallerzeugung bei gleichzeitiger Erhöhung der Ressourcenrückgewinnung und -effizienz zu erreichen, ist es sinnvoll, den konventionellen, auf einen Sektor beschränkten Managementansatz zu überdenken und stattdessen ein integriertes Management von Sektoren in Betracht zu ziehen.

Obwohl aktuelle wissenschaftliche Studien die potenziellen Vorteile eines sektorübergreifenden Resourcenmanagements von Abwasser-, Abfall- und Energieströmen anerkennen, gibt es bisher nur wenige praktische Beispiele. Somit herrscht bei Entscheidungsträgern eine Unkenntnis vor bezüglich der Ressourcen- und Energiepotenziale und es fehlen darüber hinaus praktische Empfehlungen, wie sie die unterschiedlichen biologischen Materialströme, einschließlich Klärschlamm, kommunalen Bioabfällen und landwirtschaftlichen Abfällen, besser nutzen können. Unter Berücksichtigung des Abwassermanagements als entscheidenden Kernsektor untersucht diese Forschungsarbeit das Potenzial einer integrierten Behandlung "unerwünschter" biologischen Materialströme, die insbesondere aus den Sektoren Abfallwirtschaft und Landwirtschaft stammen. Das Hauptziel dieser Forschungsarbeit war die Entwicklung eines universellen, benutzerfreundlichen Decision Support Tool (DST) zur Bewertung des Potenzials der Anwendung integrierter Infrastrukturprojekte.

Das DST ist ein Excel-basiertes Werkzeug, das Massen- und Energiebilanzen und wirtschaftliche Analysen von integrierten Abwasser- und biologischer Materialstrombehandlungsszenarien durchführt, basierend auf individuellen Benutzereingaben. Das DST ermöglicht es dem Benutzer, die stoffliche und energetische Verwertung sowie die finanzielle Projektion für sechzehn mögliche Szenarien zu bewerten, die durch Energie- und Nährstoffrückgewinnung und Wasserwiederverwendung definiert sind. Darüber hinaus erlaubt das DST dem Anwender, zwei Varianten zu bewerten: entweder die konventionelle, zentralisierte Abwasser- und organische Stoffstrombehandlung oder einen modularen Ansatz, der eine dezentrale Abwasserbehandlung für ländliche Gemeinden und eine organische Stoffstrombehandlung einschließt. Basierend auf den Benutzereingaben stellt das DST die Ergebnisse in Form von zwei Varianten eines gegebenen Szenarios schematisch dar und quantifiziert Phosphor-, Energie- und Wasserwiederverwendungspotenziale. Außerdem führt es eine Kosten-Nutzen-Analyse durch, berechnet den Kapitalwert für beide Varianten und führt eine Vergleichsbewertung durch.

Um das DST zu testen, wurde eine Fallstudienregion in Serbien ausgewählt. In dieser wurden zwischen Januar 2013 und Dezember 2014 Inputdaten aus zahlreichen Quellen gesammelt und aufgezeichnet. Dazu gehörten zum einen offizielle Daten, die von öffentlichen Institutionen, Statistikbehörden, kommunalen Aufzeichnungen und dem serbischen Finanzministerium zur Verfügung gestellt wurden. Zum anderen wurden diese Daten durch eine selbst durchgeführte Abwassermesskampagne und drei Umfragen ergänzt. Dies geschah aufgrund des Fehlens beziehungsweise der Uneinheitlichkeit bei den offiziellen Daten. Die Messkampagne wurde an den Schlüsselstellen des untersuchten Abwassersystems durchgeführt, wobei Abwasserdurchflussraten und die Konzentration von Schadstoffen gemessen wurden. Dies führte zu wichtigen Erkenntnissen, um die Zusammensetzung des Abwasserstroms, sowie die Infiltration und andere standortspezifische Bedingungen in der Fallstudienregion zu verstehen. Diese wichtigen Planungsparameter können in Zukunft auch von anderen Gemeinden genutzt werden können.

Die Forschungsarbeit zeigt, dass integrierte Lösungen, wie die hier untersuchten, einen positiven Einfluss auf Umsetzbarkeit der Kreislaufwirtschaft auf lokaler Ebene haben. Der Nutzen und die Anwendbarkeit des DST wurde anhand der serbischen Fallstudienregion getestet. Obwohl das entwickelte DST nur auf die Fallstudienregion in Serbien angewandt wurde, ist es universell unter einer Vielzahl von unterschiedlichen Bedingungen anwendbar. Das DST bietet Entscheidungsträgern ein Werkzeug, um die Vorteile eines integrierten Ressourcenmanagements zu nutzen. Darüber hinaus hilft das DST dem Benutzer besser zu verstehen, wie die verfügbaren und/oder potenziellen organischen Materialströme ihm zu Verfügung stehen und wie er das Energie- und Nährstoffrückgewinnungspotenzial berechnen kann, um vorläufige Kosten- und Finanzschätzungen durchzuführen. Das DST ist benutzerfreundlich und bietet eine schematische Visualisierung der Massen- und Energiebilanzergebnisse, die dem Benutzer einen schnellen Überblick über die Potenziale gibt.

Zusammenfassend bietet diese Forschungsarbeit einen methodischen Ansatz für die Planung integrierter Abfallwirtschaftsprojekte auf lokaler Ebene. Das entwickelte DST kann dabei helfen zukünftige Abwasser- und Umweltinfrastrukturprojekte zu planen. Seine Anwendbarkeit ist dabei nicht auf die Fallstudienregion beschränkt; vielmehr kann es in vielen Ländern und Gemeinden Verwendung finden. Um die Anwendungsbereiche als auch die Grenzen des DST besser verstehen zu können, sollten zukünftige Studien technische Erweiterungen des DST in Betracht ziehen, um neue Technologien zu integrieren; auch saisonale, zyklische und andere zukünftige Veränderungen in den Abfall- und Abwasserströmen und -zusammensetzungen werden aktuell nicht berücksichtig.

Table of Contents

List of Figures

List of Tables

Abbreviations

a	Annum
AcoD	Anaerobic co-digestion
ASP	Activated Sludge Process
ATP	Adenosine Triphosphate
BMU	Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety
BMZ	Federal Ministry for economic Cooperation and Development
BOD	Biological Oxygen Demand
C	Carbon
CAP	Common Agriculture Policy
CHP	Combined Heat and Power (co-generation)
CMC	Component Material Categories
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
CSR	Case Study Region
CW	Constructed Wetlands
d	Day
DM	Dry Matter
DST	Decision Support Tool
EBRD	European Bank for Reconstruction and Development
EC	European Commission
EEA	European Environmental Agency
EIB	European Investment Bank
EP	European Parliament
EPA	United States Environmental Protection Agency
EREP	European Resource Efficiency Platform
EU	European Union
EUROSTAT	European Statistical Office
FAO	Food and Agriculture Organization
FOG	Fats, Oil and Grease
FW	Fresh Weight
GAIN	Global Agricultural Information Network
GDP	Gross Domestic Product
GHGs	Green House Gases
GIZ	Die Deutsche Gesellschaft für Internationale Zusammenarbeit

GRS	Government of the Republic of Serbia
H_2	Hydrogen
HRT	Hydraulic Retention Time
HSW	High Strength Waste
IFC	International Finance Corporation
Inh.	Inhabitants
IPA	Instrument for Pre-Accession Assistance
IPCDR	International Commission for the Protection of the Danube River
IWRM	Integrated Water Resource Management
K	Potassium
L_d	Daily load
MAP	Magnesium Ammonium Phosphate
MBT	Mechanical Biological Treatment
MC	Measurement Campaign
MDGs	Millennium Development Goals
MFM	Material Flow Management
Mil.	Million
MSW	Municipal Solid Waste
N	Nitrogen
NO_3-N	NItrate-Nitrogen
NH_4-N	Ammonium-Nitrogen
NPV	Net Present Value
N_{tot}	Total Nitrogen
O&M	Operation and Maintenance
oDM	Organic Dry Matter
OLR	Organic Loading Rate
OMSW	Organic Municipal Solid Waste
P	Phosphorus
PE	Population equivalent
PO_4-P	Orthophosphate-Phosphorus
PPS	Purchasing Power Standards
PS	Pumping Station
P_{tot}	Total Phosphorus
PUC	Public Utility Company
Qd	Daily flow
$Q_{d,av,pM}$	Daily Average Wastewater Flow (for the observed period)

$Q_{Dom,aM}$	Annual Mean Domestic Wastewater Flow
$Q_{DW,pM,max}$	Daily Maximal Dry Weather Flow (for the observed period)
$Q_{DW,pM,min}$	Daily Minimal Dry Weather Flow (for the observed period)
$Q_{DW,s,pM}$	Daily Dry Weather Flow (for the observed period)
$Q_{Ind,aM}$	Annual Mean Industrial Wastewater Flow
$Q_{Inf,pM}$	Infiltration Flow
$Q_{WW,aM}$	Annual Average Wastewater Flow
RELV	Serbian Wastewater Emission Limit Regulation
SBR	Sequence Batch Reactor
SDGs	Sustainable Development Goas
SEE	South and East Europe
SEPA	Serbian Environmental Protection Agency
SORS	Statistical Office of the Republic of Serbia
t	Ton
TFS	Total Fixed Solids
TS	Total Solids
TSS	Total Suspended Solids
TVS	Total Volatile Solids
UBA	German Environmental Agency
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UWWTD	Urban Wastewater Treatment Directive
VFA	Volatile Fatty Acids
WAS	Waste Activated Sludge
WHO	World Health Organisation
WWT	Wastewater Treatment
WWTP	Wastewater Treatment Plant

1 Introduction

1.1 Research Aims and Objectives

Current economic models function in a linear manner – extract → produce → use → dispose – with little or no consideration about resulting environmental pollution (Sauve et al., 2015; Korhonen et al., 2018). Such an economical model, termed “linear economy,” is premised on continuous growth reliant on increased recourse consumption. Due to the unsustainable nature of the present economic system, Europe has begun the transition towards a so called “Circular Economy”. The term Circular Economy might be most simply explained as “an economy where nothing is wasted” and “a system which is restorative by intention” (Genovese et.al, 2017). Circular Economy aims to maximize and recirculate material and energy flows within a defined system while decreasing the need for new raw materials and diminishing pressure on the environment.

Water supply and wastewater treatment are recognized as the most significant contributions to public health over the past 150 years, as well as one of the main engineering contributions to society in the 20th century (Daigger et al., 2017). However, in current times conventional wastewater management is no longer entirely suitable for today’s modern society, as conventional management relies predominantly on removing pollution, eliminating associated health risks, and preserving the recipient ecosystem; while the potential of wastewater as a source of reclaimed water, energy, nutrients and organic matter is typically neglected (UNESCO, 2017). Thus, Circular Economy objectives seek to apply new solutions that guarantee safe discharge and preservation of the environment while remaining resource and energy efficient, and acceptable and affordable for end-users.

The necessity of such a paradigm shift in wastewater management towards resource and energy efficiency and solutions that simultaneously address multiple mediums and create manifold benefits has been recently recognized by notable academic peers (Maktabifard et al., 2018, Daigger et al., 2017, Olsson, 2015, Van der Hoek et al., 2016, Van Loosdrecht and Brdjanovic, 2014, Solomou et al., 2014). In practice, however, integrated management of associated sectors – for example wastewater and waste – are not yet state-of-the-art solutions, even though technologies necessary for integrated concepts, such as anaerobic digestion, have proven to be reliable. Here, the biggest challenge remains in the planning and conceptual phase. Decision makers are typically unaware of certain resources available in their “own backyard” and may even view them as undesirable and/or expensive “waste” flows (e.g., organic waste and sewage sludge); decision makers furthermore often lack the tools necessary to support them to plan and implement new, more innovative concepts.

The purpose of this study is to assess the added value in applying integrated wastewater-organic material flows concepts (hereafter termed “integrated concepts”) on the local level and examine how these concepts relate to achieving Circular Economy principles. The guideline herein is defined as the activation and joint processing of organic “waste” flows – those that are currently unutilized and generally considered end products – with the joint aims to: i) offset resource depletion by limiting energy and material inputs, and ii) reduce environmental impact by decreasing waste generation (Fig. 1.1). The overall objective is to create and test an easily deployable Decision Support Tool (DST) that can serve as an initial step to plan and implement integrated solutions on the local level. A selected case study is used to demonstrate the tool’s functionality and applicability. In that regard, this research seeks to answer the following questions:

1. What are the main drivers, benefits and bottlenecks to mainstream integrated wastewater and organic material flows management?
2. How can the activation of regionally available organic material flows and their integrated management support the transition towards a Circular Economy?
3. How to support and facilitate decision making to apply integrated solutions on a local level?
4. What data are necessary for a decision making process and how can they be collected? Here, the research relies on a Case Study conducted in Serbia.
5. How can the developed tool support decision makers to evaluate their own potential and resources for integrated resources management?

1.2 Research Scope

Fig.1.1 illustrates the scope of the research. The focal point is the municipal wastewater management sector and includes its inter-connection with other associated sectors defined by a common material throughput (e.g. organic matter, phosphorus). Thus, the system boundaries extend to waste management and agriculture sectors (Fig.1.1).

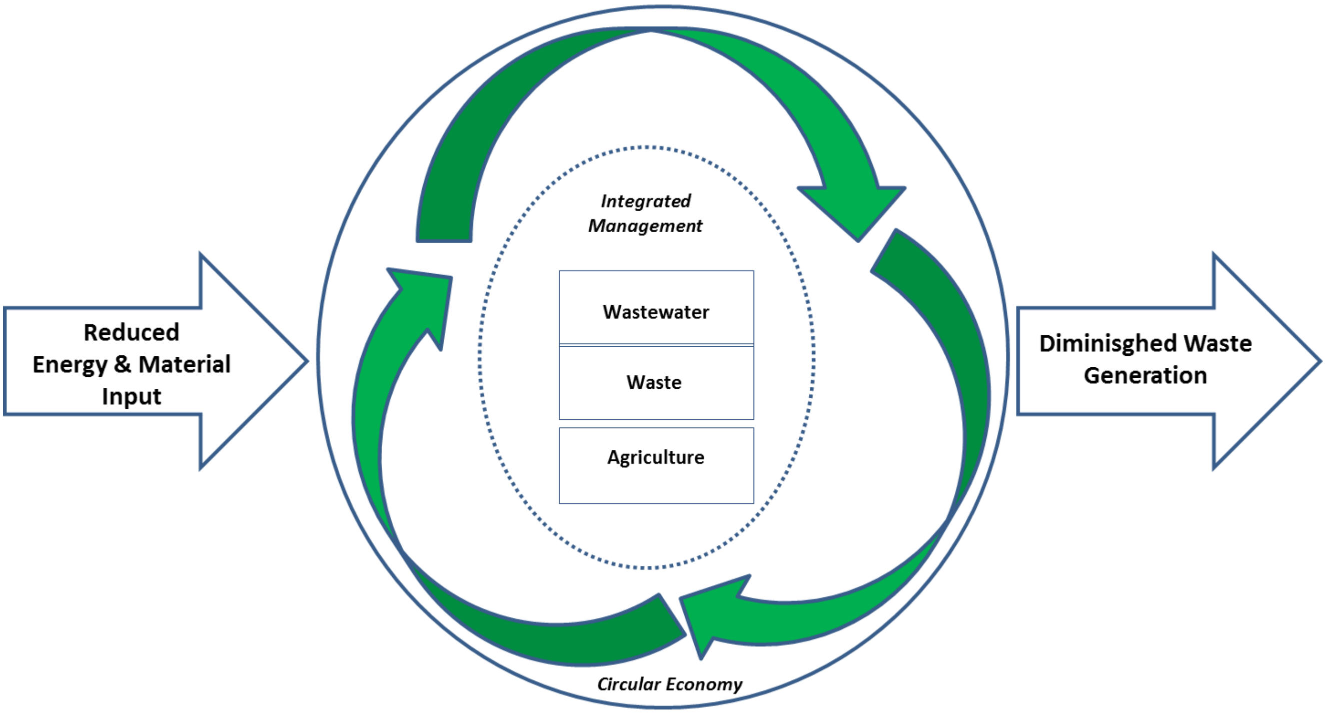


Fig.1.1: Research scope – integrated management of organic material flows within the Circular Economy Principles.

Traditionally, the sectors represented in Fig.1.1 are managed independently. Such a management practice is unsustainable because the effect of energy and material consumption on the input side, as well as the amount of generated waste products on the output side, is unsuitably great and in turn negatively impacts the environment. To optimize the circularity of energy and resources, this research foresees that the conventional approach of each sector's independent management is exchanged with a more integrated management approach. Thus, as shown in Fig.1.2, the organic material flows of interest in this research include those from the sectors of wastewater, waste and agriculture, and more specifically includes sewage sludge, bio-waste and agricultural waste residues (agro-waste).

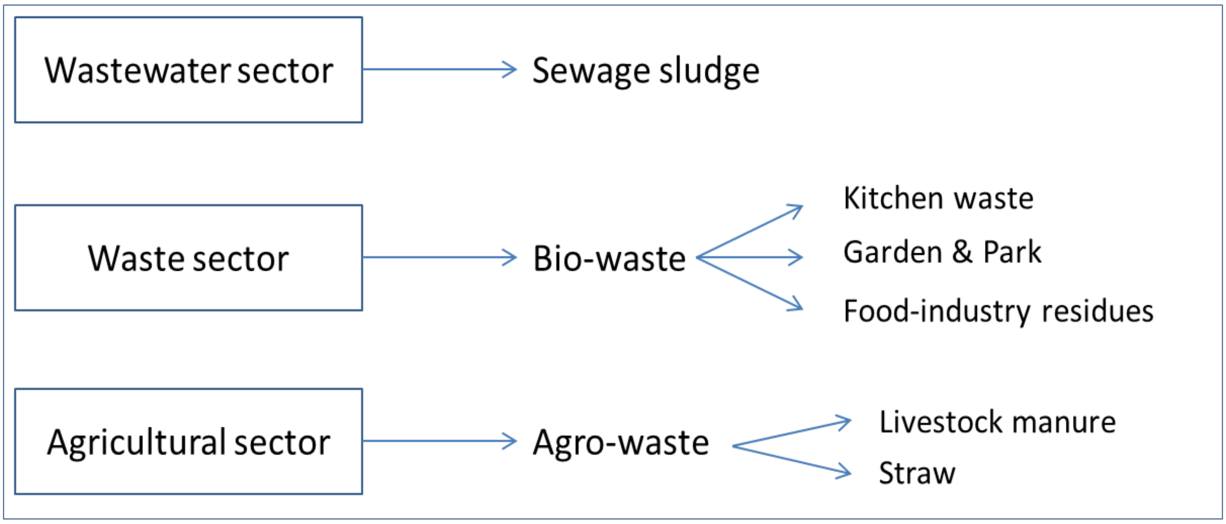


Fig.1.2: Sectors and particular material flows of interest included into the scope of the research.

Looking at Figure 1.2, we define the three types of waste from the respective sectors:

- **Sewage sludge (wastewater treatment):** “Residual sludge from sewage plants treating domestic or urban wastewaters and from other sewage plants treating wastewaters of composition similar to domestic and urban wastewaters.” (Article 2, Directive 86/278/EEC).
- **Bio-waste (waste sector):** “Biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants. Other biodegradable flows such as agricultural residues, manure, sewage sludge, textile, paper and process wood are considered as separated flows.” (Article 3, Waste Framework Directive, 2008/98/EC).
- **Agro-waste (agricultural sector):** Livestock manure and straw. Manure includes excrements (urine and feces) produced by household livestock. Straw includes the residue of cereal or oilseed crops remaining on the fields post-harvest; it typically consists of the plant stem but may include leaves and chaff.

1.3 Dissertation Outline

To provide the reader a preliminary overview of this study, following is a short outline of the overall dissertation content:

- **Chapter 1, Introduction:** Chapter 1 (current section) reviews research aims, objectives and scope.
- **Chapter 2, Literature Review:** Chapter 2 overviews the theoretical background associated with the research topic, beginning with a description of drivers for integrated resource management and an analysis of current wastewater and waste management practices on the European level. It continues with an analysis of opportunities for integrated resources management. An overview of relevant integrated concepts worldwide, as described in the scientific literature is then presented, including key constraints for implementing these integrated solutions. Lastly, as the case study used for this research is located in Serbia, the local Serbian perspective regarding integrated management is analysed in depth.
- **Chapter 3, Material and Methods:** Chapter 3 summarizes the data, materials and methods used for the research, beginning with a description of the methodological approach and the case study used for the research. It then details the conducted case study field work methodology and data collection, and lastly elaborates the development of the DST.
- **Chapter 4, Results and Discussion:** Chapter 4 presents the results of the conducted research, first presenting the evaluated results of the field work; and second, debating the results and interpretation of the developed DST. The results of the tested case study evaluated data by the developed tool are furthermore interpreted and further implications of tool application are discuses. Finally, the chapter summarises the limitations of the developed tool.
- **Chapter 5, Summary and Outlook:** Chapter 5 concludes the outcome of the research, summarizes the findings related to the research questions, and provides practical recommendations for future study and improvement.

2 Literature Review

2.1 Drivers of Integrated Resource Management

2.1.1 Need for New Pollution Control Approach – An Environmental Driver

Over the period of the industrial revolution, populations migrated from rural areas to towns and urban areas, compressing into increasingly limited spaces, resulting in local water pollution challenges and water-borne diseases. As a result, safe potable water supply systems were installed. This lifesaving solution significantly improved human health, but in turn created a new challenge, namely wastewater. In the late 19th and early 20th century, this challenge necessitated the field of sanitary engineering as a separate engineering branch (Daigger et al., 2017, Schneider, 2011, Sedlak, 2014). As the logical next development step, wastewater began being collected and evacuated to a central treatment facility (WWTP). Schneider (2011) defines a WWTP as an "industrial ecosystem, and an important part of urban infrastructure" (Schneider et al., 2011). According to Odum (1971) the ecosystem is "any unit that includes all of the organisms (i.e., "the community") in a given area interacting with the physical environment so that the flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (i.e., exchange of materials between living and non-living parts) within the system" (Odum, 1971). In a WWTP bacteria consume organic matter from wastewater to support their growth and metabolise it to carbon dioxide, while converting protein and organic nitrogen to ammonia, nitrate and nitrogen gas. As such, WWTPs effectively function on the same principle as natural ecosystems, but with "human intervention in its creation and management" (Schneider et al., 2011).

The basic assumption in conventional wastewater management is that the environment can handle pollution to a certain extent, so long as effluent is returned to the environment in line with established limits on pollutant emissions and discharges. Over the last 60 years, we have seen rapid development of environmental technologies and conventional pollution control measures, which have significantly improved human well-being, as well as environmental protection (Daigger et al., 2017). Presently, conventional wastewater management (“collect and forget”) is no longer entirely suitable for society due to its limited perspective and fragmented view. Conventional wastewater infrastructure is designed only for a limited portion of the pollution of a region – the wastewater itself – while if we take a broader viewpoint, a more integrated approach linking different sectors under joint management can present more efficient solutions. This limited perspective over the past decades has resulted in the construction of rigid infrastructure designed to projected capacities. Over time, management of such rigid systems becomes a challenge in the face of evolving external factors such as population, type and concentration of pollution, weather conditions, and other factors. An additional constraint of conventional pollution control is that it does not consider other negative consequences that might be caused by additional treatment steps and resource (energy and chemicals) consumption to maintain control limits. Aside from their use, these valuable resources are also lost during treatment processes. For instance, by using biological nitrogen removal in WWTPs, we eliminate nitrogen from the wastewater, but create a by-product, N_2O, which is a powerful greenhouse gas (GHG) and which accounts for ca. 10% of GHGs emissions (Deslover et al., 2012).

The intensive energy demand of WWTPs has been discussed by numerous scholars in recent years (e.g. Ganora et al., 2019, Schopf et al., 2018, Maktabifard et al., 2018, Liu et al., 2016, Gude 2015, Venkatesh et al., 2014). WWTPs are highly energy intensive, relying on fossil fuels and other natural resources for operation, with these costs of consumption passed along to the users. Electricity is the main energy resource of WWTPs, accounting for 25-50% of the operating costs (Foladori et al., 2015, Panepinto et al. 2016). Within the treatment process itself, the most energy intensive operations are secondary treatment due to aeration (55-70%); primary and secondary sludge settling due to pumping (16%); and sludge dewatering (7%) (Husmann, 2009) On the EU-28 level, annual urban WWTP electricity demand is estimated to be ca. 25,000 GWh, or ca. 0.8% of the EU-28 overall electricity consumption (Ganora et al., 2019).

2.1.2 Social Drivers

Global population increase and the associated increases in resource consumption and food demand are the main contributing factors that have changed the paradigm in environmental infrastructure planning. As Fig. 2.1 and Fig. 2.2 demonstrate, from 1970-2010 the global population doubled, while the global economy tripled.

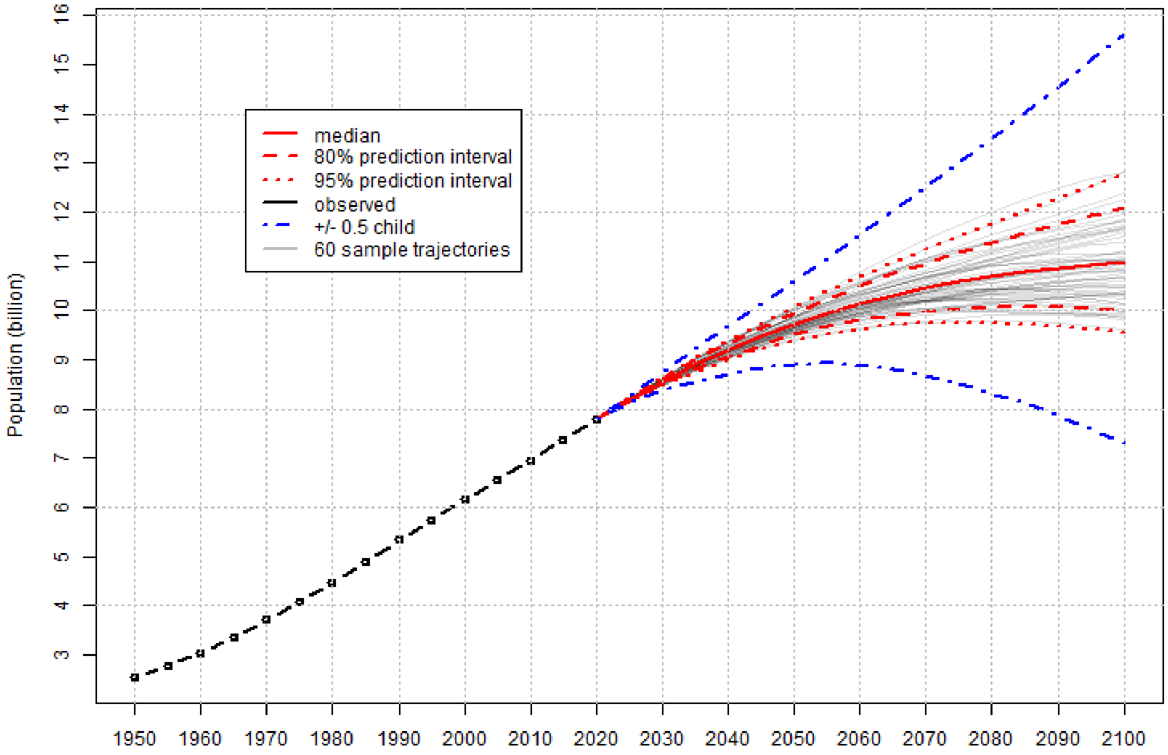


Fig. 2.1: Global population increase and projection for the future.

Source: (UN, 2019)

The United Nations (UN) has estimated that this trend will likely continue, increasing the world population to 9.7 billion in 2050 and 11 billion in 2100 (all values medium variants) (UN, 2019). Consequently, it is projected that additional land will be required for housing, industry, and infrastructure development, which is most likely to take place on arable land, thereby resulting in even higher levels of resource consumption. Further, global materials consumption is expected to double in the next forty years, increasing annual waste generation by 70% over the next thirty years (EC, 2020a).

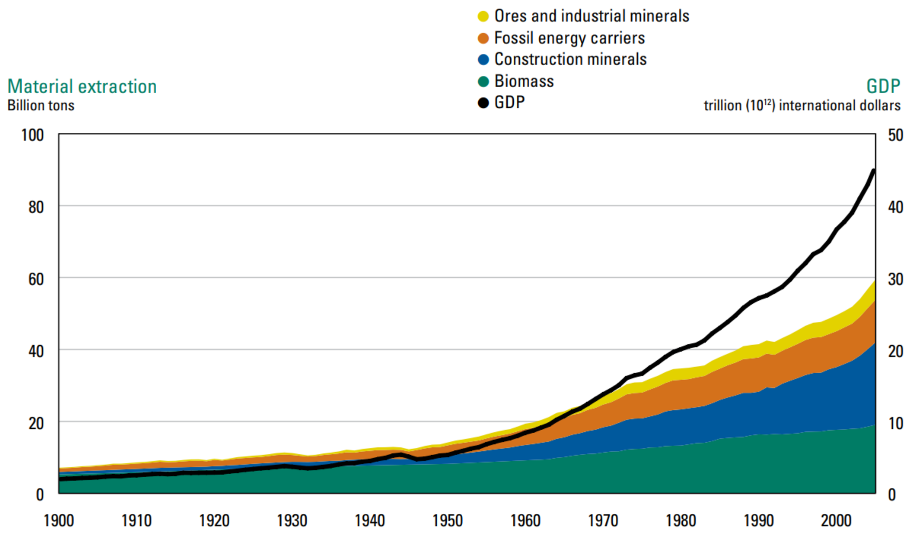


Fig. 2.2: Relationship between economic growth and material and energy extraction.

Source: (UNEP, 2011)

This trend also poses existential questions regarding food production and security. The nutrients phosphorus, nitrogen and potassium are the primary components of fertilizer and necessary ingredients for commercial agriculture. According to Food and Agricultural Organization (FAO), the global nutrients demand for fertilizer production has been constantly increasing (except during the global economic crisis in 2009) and is expected to exceed 200 Mil. tons in 2022 (FAO, 2020).

Phosphorus is a limited, irreplaceable element which is essential for all form of life. It is a vital component of DNA and RNA and a key element of the molecular energy supplier adenosine triphosphate (ATP), the molecule that transports energy within cells. As phosphorus is limited and irreplaceable, its inefficient management could restrict sustainable food supply in the future. The U.S. Geological Survey (2019) published that the global consumption of phosphates in 2018 was 47 Mil. tons and projected to increase by 7.5% by 2022. The availabilities of phosphorus and potassium are critical, as they are obtained from mineral deposits. Although not scare elements on Earth, phosphorus has been become limited due to disturbances in its natural cycle: phosphorus passes through interconnected inorganic (agriculture → soil → erosion → transport to surface water systems → sedimentation → tectonic uplift → phosphate rocks → fertilizer) and organic (agriculture → plants → humans/animals → organic waste) cycles. The natural cycle is disturbed when the human and animal excrements are not re-used in agriculture, but instead disposed of together with sewage sludge from the wastewater treatment process. Therefore, the activation and recovery of phosphorus is of crucial importance to society.

As Fig. 2.3 shows, 95% of phosphorus deposits are found in just 10 countries, with three North African countries accounting for 80% of global deposits (UBA, 2018). Even though China‘s phosphors deposit accounts for only 4% of the world’s reserves, it is the largest mining country, accounting for more than half of world’s annual phosphorus mining (UBA, 2018). In Europe, the only phosphorus deposits are in Finland, which accounts for only ca. 1% of global reserves. Europe currently faces a phosphorus dependency of more than 90%, with Russia and Morocco the main suppliers. Germany, for example, is entirely dependent on imports; for the economic year 2016-2017, 231,100 tons of P_2O_5 were demanded for mineral phosphate fertilizers (UBA, 2018). This situation presents serious political and economic risk. As a result, in 2014 the European Commission declared phosphate rock as one of the 20 critical resources for the EU (EC, 2014a) and secures the necessity for autonomous sourcing, for instance through recycling (EC, 2017c).

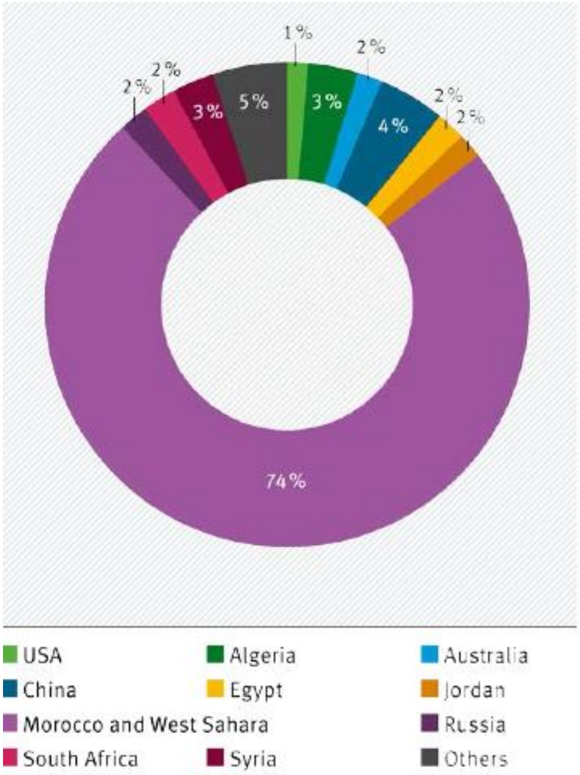


Fig. 2.3: Mined phosphorus worldwide (2016).
Source: (UBA, 2018)

Phosphorus demand is also increasing globally due to population growth and changes in eating habits towards more meat and dairy products. The industrialization of agriculture, termed the "Green Revolution" or "Third Agricultural Revolution", has led to remarkable increases in food and crop yields, both directly increasing human food supply and dramatically increasing crop production to support more meat- and dairy-intensive diets. However, The Green Revolution was based on the presumption that nutrients are available in limitless quantities (Popp et al., 2012); and phosphate rock – a key resource necessary to sustain the high productivity of today's agriculture – was perceived as an inexhaustible source of concentrated phosphorus (Cordell et al., 2009).

This attitude changed during the food crisis in 2008, when the phosphate rock commodity price peaked at ca. 450 US$ per ton, eight times higher than at the end of the 1990s and beginning of 2000 (Fig. 2.4). Since 2014, the commodity price of phosphate rock has roughly stabilized at ca. 100 US$ per ton. In 2017, 58 Mil. tons of P_2O_5 were mined worldwide (UBA, 2018). The U.S. Geological Survey assumes an annual increase in global phosphate demand of more than 2%, equating to more than 5 Mil. t/a. Cordell et al. (2011) estimate that peak phosphorus will occur between 2051 and 2092. Yet, scholars offer varying estimates for how long phosphate deposits can cover global agricultural demand, ranging from the high end of 130 years (Rosmarin, 2004), 115 years (Elsner, 2008), to 50-100 years (Larsen et al., 2007; Van Vuuren et al., 2010).

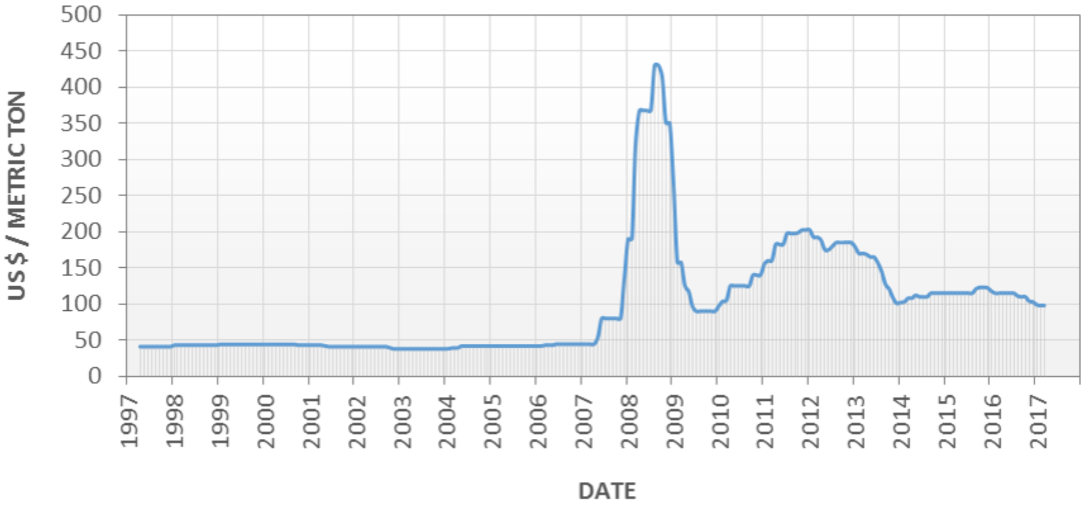


Fig. 2.4: Phosphate rock commodity price 1997-2017.
Source: (World Bank, 2017)

The paradigm change in science toward integrated and inter-sectorial thinking is termed “Nexus”, which can be traced to the 1980s when the United Nations University emphasized the importance of food and energy management during the international symposium “Food, Energy and Ecosystem” held in Brasilia, Brasil (1984) and New Delhi, India (1986) (Endo et al., 2017). Subsequently, in the early 2000s, scholars concurred with the importance to interlink water and energy. Finally, in 2011 at the Bonn Nexus Conference, held prior the UN Conference on Sustainable Development (Rio+20), the “Water-Energy-Food Nexus” was introduced. Since then, “Nexus” has been generally accepted by scholars and described as a “promising approach” (Allan et al., 2015) and “new thinking” (Ringler et al., 2013).

The Nexus concept is used worldwide in different interpretations depending on regional agendas (Ringler et al., 2013). It connects stakeholders of different sectors and levels to achieve sustainable development (Endo et al., 2017). Some authors argue that the Nexus approach has been introduced following the failure of similar concepts, such as integrated water resources management (IWRM) (Endo et al., 2017, Al-Said and Elagib, 2017). In both the Nexus and IWRM concepts, the water sector remains the center of attention, whereas Nexus goes further, as it “facilitates collaboration with other sectors by encouraging resource-use efficiency” (Endo et al., 2017), and IWRM focuses strictly on the water sector. Nexus, therefore, is a holistic way of thinking as it does not favor one single pillar but rather fosters synergies across multiple sectors.

Although recognized among scholars and used by politicians in discussions around sustainability, the “governance side” of Nexus still needs to be further improved (Venghaus and Hake, 2018). The political and governance aspects of Nexus present particular challenges, as different authorities are generally responsible for the different Nexus pillars, each having different priorities and interpretations of the approach (Venghaus and Hake, 2018). Policy makers expect that scientists continue to develop and refine the tools for Nexus implementation, while Circular Economy provides an overall framework for implementing Nexus-driven solutions; however, the paradigm should be further integrated within government decision support processes, and “translated through more case study-based recommendations” (Al-Saidi and Elagib, 2017).

2.1.3 Policy Drivers

In Europe, the necessity to achieve integrated resource and energy concepts has been established through the adoption of the Circular Economy concept as an overall policy tool, augmented by EU climate objectives. The new European growth strategy, the “European Green Deal”, established the political commitment to achieve EU climate neutrality by 2050. The strategy establishes a roadmap for the EU to become a “fair and prosperous society, with a modern, resource-efficient and competitive economy … where economic growth is decoupled from resource use.” This ambitious task is to be achieved by transitioning from a linear economic system or “flow-through society” into a durable recycling or “circular economy society” (EC, 2020a).

The Ellen MacArthur Foundation illustratively presented the Circular Economy concept shown in Fig. 2.5. As the figure shows, Circular Economy builds outward from the linear economy system of “take, make, dispose” (center of figure) and indicates the possibilities of closing the loops, decreasing demand for primary resources while minimizing waste generation. Circular Economy aims to limit and optimize material and energy throughputs to levels that nature can tolerate, and to decouple economic growth and development from the consumption of finite resources. The Circular Economy concept covers all aspects of the economic system: “resource extraction through production, storage and consumption, ending with disposal or ideally recycling” (EP, 2017a).

Although the term Circular Economy is broadly applied in discipline and in practice, it has no singular definition among the scholars. Kirchherr et al. (2017) reviewed 114 Circular Economy descriptions and proposed the following:

“A circular economy describes an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations” (Kirchher et al., 2017).

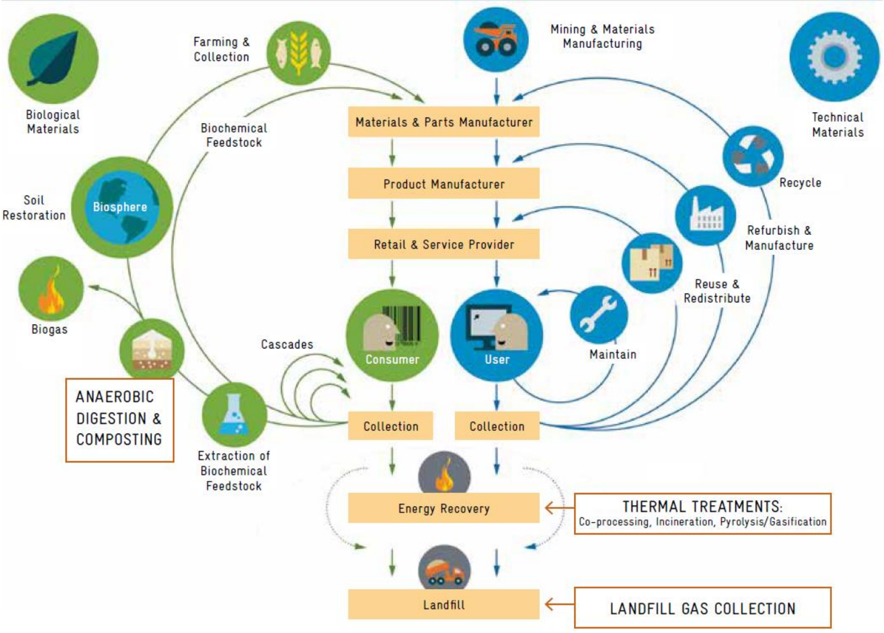


Fig. 2.5: The principle of the Circular Economy.

Source: (Ellen MacArthur Foundation, 2013)

As the definition states, the overall aim of Circular Economy is to achieve sustainable development. Its environmental objective is to decrease raw material and energy inputs and waste and emissions outputs through application of material cycles and renewable-based energy cascades. Its economic objective is to reduce the costs of raw material and energy on the input side, while minimizing waste generation and associated emissions control costs on the output side. The social objective of Circular Economy is to increase employment, stimulate participative democratic decision-making, and make more efficient use of material capacity through cooperative and community users (groups using the value, service and function) as opposed to consumer culture (individuals consuming physical products) (Korhonen et al., 2018).

The foundation of the Circular Economy in Europe primarily emerged in Germany in the 1990s with the Circular Economy and Waste Act (KrW-/AbfG, 1994). The European community adopted it later, with targets set by the Waste Framework Directive (2008/98/EC), the principal legislative framework in the European Union for waste management. According to Article 3 of the Waste Framework Directive, waste is defined as “any substance or object which the holder discards or intends or is required to discard” (2008/98/EC). The Waste Framework Directive has three core principles:

- “Polluter Pays Principle”: Ensures that costs of waste prevention, control and environmental protection are incorporated in the costs of product/good.
- “Waste Hierarchy Principle”: Ranks waste management options in order of priority and according to sustainability principles (Fig. 2.6).
- “End of Waste Status”: Defines when waste ceases to be waste (e.g., after recovery).

The second governing waste management legislation at the European level is the Landfill Directive (31/1999/EC), which establishes all requirements for waste and landfills. The Directive stipulates that within 15 years following its implementation (i.e. 2014) biodegradable waste must not exceed 35% of the amount (by weight) of biodegradable municipal waste produced in 1995. In addition, most national regulations in compliance with the Landfill Directive do not allow landfilling waste with more than 5% biodegradable carbon content.

From the legislative perspective, bio-waste management is regulated by two key waste management Directives, plus the Circular Economy package. The first, Waste Framework Directive obliges the Member States to adopt measures to encourage separate collection of bio-waste. The second, Landfill Directive, obligates the diversion of bio-waste from landfills. The Landfill Directive, however, did not regulate which specific waste treatment facility should be applied by the Member States, resulting in States generally applying the cheapest and simplest treatment methods. Thus, in the case of economically weaker countries, landfilling has normally been applied, while more prosperous countries applied incineration as a waste management option (see Chapter 2.2 for further analysis).

The clarified postulation of Circular Economy policy has been installed only recently. In 2014 the EC published the Communication, “Towards a Circular Economy: A Zero Waste Programme for Europe”. This Communication established the visionary waste management “close-the-loop” approach (EC,2014a), aiming to convert waste flows into resources and, thus, substitute primary resource depletion. As a next step, in 2015 the EC adopted an EU Action Plan for Circular Economy aiming to reach

Sustainable Development Goals (SDGs), especially SDG 12 – Promote Sustainable Consumption and Production Patterns (EC, 2015). The Action Plan states that “waste management plays a central role in the circular economy” and recognises that the waste management sector needs further optimisation (EC, 2015). Thus, it is important that waste management options are harmonised with the EU waste hierarchy; consequently, in 2017 the Commission published the Communication, “The Role of Waste-to-Energy in the Circular Economy” which aims to “ensure that the recovery of energy from waste in the EU supports the objectives of the Circular Economy Action Plan and is firmly guided by the EU waste hierarchy” (EC, 2017b). With that, Communication the Commission associates waste management options to the hierarchy shown in Fig. 2.6.

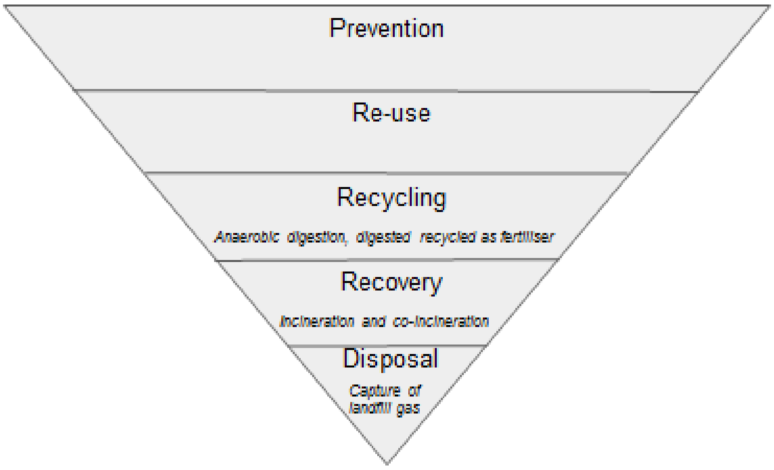


Fig. 2.6: The waste hierarchy and waste-to-energy processes.

Source: (Modified after EU, 2017)

Circular Economy directs that the “value of products, materials and resources is maintained for as long as possible, minimising waste and resource use” (EC, 2015). Incineration and waste disposal result in GHGs, while offering limited to no options for resource recovery (Long et al., 2017). Therefore, transition to Circular Economy is possible only if the principle of waste hierarchy is respected. As Fig. 2.6 shows, anaerobic digestion is akin to “recycling” and thus has priority over other waste-to-energy processes such as incineration or landfill gas capture.

In 2018, building on previous advancements, the Circular Economy Package was adopted, establishing the following targets (EC, 2018):

- Municipal waste reuse and recycling targets adopted as follows: 55% by 2025; 60% by 2030; and 65% by 2035.
- By 31 December 2023, bio-waste is either separated and recycled at its source, or is collected separately and not mixed with other types of waste.
- By 2030, all waste suitable for recycling or other recovery, in particular municipal waste, shall not be accepted in a landfill.
- By 2035 the amount of municipal waste landfilled is reduced to 10% or less of the total amount of municipal waste generated.

The main characteristic of revised waste legislation is that it considers a complete economic cycle of waste products, and in turn provides a long-term pathway for waste recycling. In accordance with Waste Hierarchy and the revised waste legislation (i.e., recycling targets), bio-waste treatment facilities based on anaerobic digestion are prioritized. Thus, from 2027, municipal bio-waste entering aerobic or anaerobic treatment may only be counted as recycled if, in accordance with Article 22, it has been collected separately or separated at its source.

The main policy instruments of the EU wastewater legislation are the Urban Wastewater Treatment Directive 91/271/EEC (UWWTD) and the Water Framework Directive 2000/60/EC. The Water Framework Directive is the governing legislation on water management in the EU; it aims to integrate water resource management and obligates the Member States to reach “good status” on all their water bodies through the implementation of River Basin Management Plans. In the wastewater management sector, the UWWTD is the primary regulation, complementing the Water Framework Directive. UWWTD regulates wastewater collection and treatment in urban communities with more than 2,000 population equivalents (PE) by setting pollution emission limits. It envisions advanced wastewater treatment with nutrient removal above 10,000 PE, especially in sensitive areas. UWWTD is thus the main policy instrument for controlling discharges of nitrogen and phosphorus from point sources.

Diffuse nutrient pollution of water bodies is caused in large part by over-fertilisation in agriculture operations. This problem is addressed by Nitrate Directive 91/676/EEC, with the overall aim to "protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices" (European Council, 1991). This problem is regulated by strict guidelines for the management of organic and inorganic nutrients, placing restriction on storage, application rates and timing of land applications. These rules are compulsory for farmers located in nitrate-vulnerable zones and include a limit of 170 kg N/(ha*a) from livestock manure. The Nitrate Directive's impact goes beyond its scope to protect water bodies, as it also regulates livestock management and fertilizing practices, supports climate change abatement, and is a crucial policy instrument for regulating digestate from anaerobic digestion.

The new Circular Economy Action Plan (2020) emphasises the importance to develop an "Integrated Nutrient Management Plan" to ensure "more sustainable application of nutrients and stimulating the markets for recovered nutrients" (EC, 2020a). The Action Plan further supports cross-border collaboration to foster the development of secondary raw materials. In addition, the revised EU Fertiliser Product Regulation (EC 2019/1009), adopted in May 2019, supports the transition to circular agriculture by supporting the manufacture of fertiliser for EU markets from secondary materials such as agricultural by-products and bio-waste, and facilitates the conversion of bio-waste into fertilizer, thus reducing the dependency of European farming on imports of mined and fossil raw materials, including phosphate rock. The Regulation defines eleven categories of Component Material Categories (CMCs) which are the only eligible constituents of fertilizer products (Annex II, EC 2019/1009). Specific requirements for each of the CMCs apply; it is noteworthy that digested sewage sludge cannot be used for fertilizer production, due to the potential presence of heavy metals, faecal coliform, and other contaminants. Fresh crop digestate (CMC 4) and digestate from sources other than fresh crop digestate (CMC 5) are eligible fertilizer components. Per CMC 5 fertilizers may utilize digestate from anaerobic digestion of bio-waste "resulting from a separate bio-waste collection at source". The Regulation shall be applied from 16 July 2022 (Regulation 2019/1009).

Renewable Energy Directive 2009/28/EC may be viewed as an overall policy instrument relevant for integrated projects. It establishes policy for the production and promotion of renewable energy sources within the EU. In 2018 the revised Directive

2018/2001/EU entered into force, increasing targets previous “20% by 2020” to “32% by 2030”. In addition, as a part of the European Green Deal, in 2020 the EC established an additional two targets for 2030L 40% reduction in GHG emissions compared to 1990 and at least 32.5% improvement in energy efficiency.

2.2 Prospects of European Wastewater and Waste Management

For disusing the wastewater and waste management prospects in Europe, EUROSTAT the statistical online database of the EU was used. Year 2016 was used as a baseline year (Eurostat access in August 2020) as most actual year for which the data was available for the most of European countries.

2.2.1 Wastewater Management

Sustainable wastewater management is a crucial goal in global development agendas, being a prerequisite for health, economy, well-being, and environmental protection of any country. Although a legal framework has existed for some time, wastewater management differs significantly among EU countries, depending primarily on the economic strength and living standards of individual countries.

For comparison of living standards on the European level, gross domestic product (GDP) per capita, adjusted for differences in price levels and purchasing power standards (PPS), is used, where the EU average is set to equal 100. As seen in Fig. 2.7, there are clear differences in the living standard between European states. European countries with the highest living standard include the Scandinavian countries; Benelux (Belgium, Netherlands and Luxembourg); and some central European countries (Austria, Germany and Switzerland). These same countries also have the highest proportion of the population connected to at least secondary wastewater treatment (Fig. 2.8), with the highest rate of ca. 100% having already been reached by Austria, the Netherlands and Luxemburg (2016). The economically weaker European countries located mainly in the south and east Europe (SEE)[1], have considerably weaker wastewater infrastructure development (Fig. 2.8).

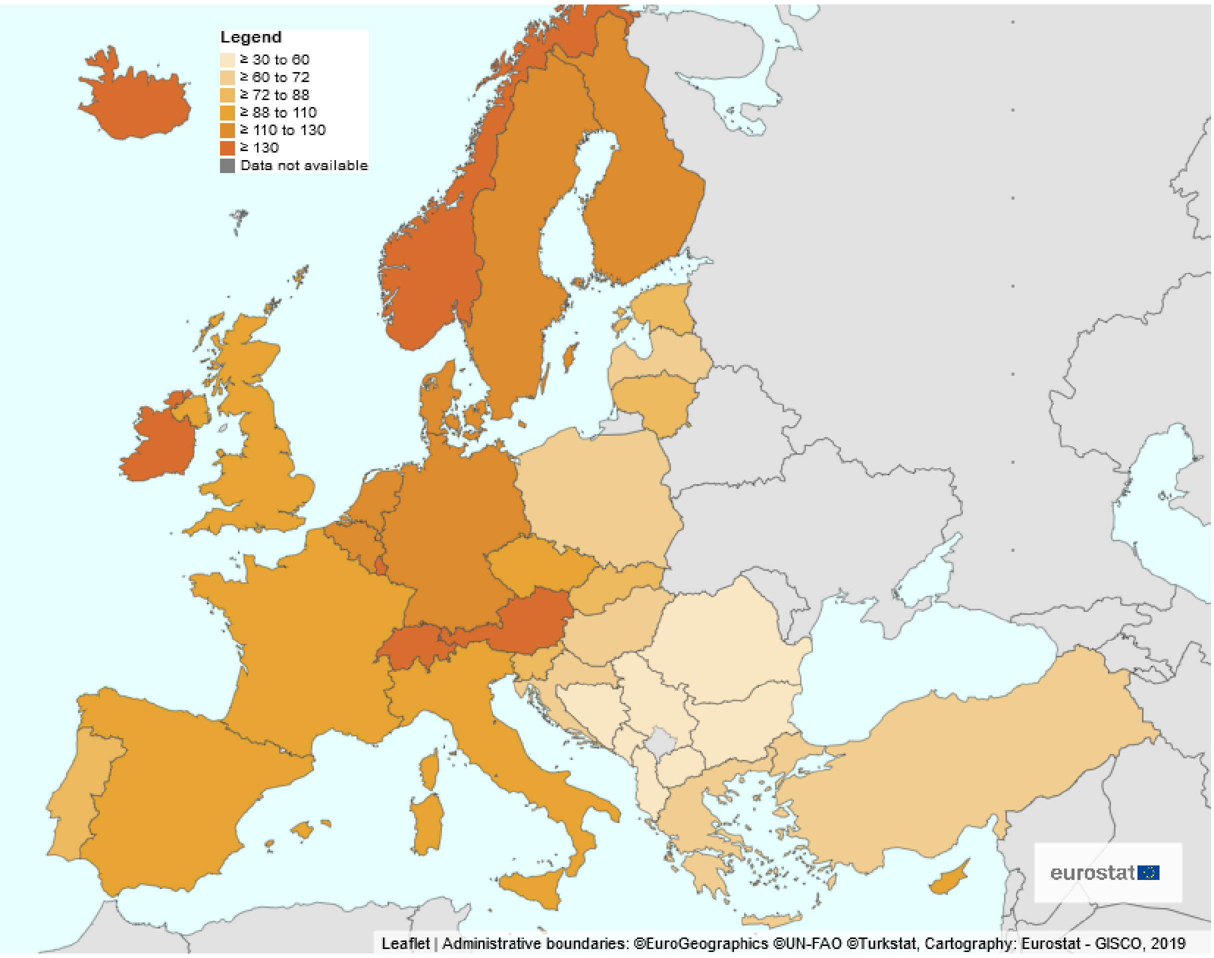


Fig. 2.7: Overview of living standard differences in European countries expressed as per capita GDP in PPS, 2016.

Source: (Eurostat, 2020)

In Bulgaria and Slovenia ca. 60% (2016) of the population is connected to secondary wastewater treatment, while in Romania and Croatia only ca. 44% (2016) is connected. Considerable disparities and lagging wastewater treatment capabilities are prevalent in countries including Serbia (12%; 2016) and Albania (7%; 2016). The

---

[1] Analysis include the following CEE countries: Bulgaria, Greece, Croatia, Romania, Slovenia, Albania, Serbia, and Bosnia& Herzegovina. Due to data unavailability, excluded are Kosovo, Montenegro and North Macedonia.

only exception in the SEE region is Greece where 93% of the population is connected to at least secondary wastewater treatment.

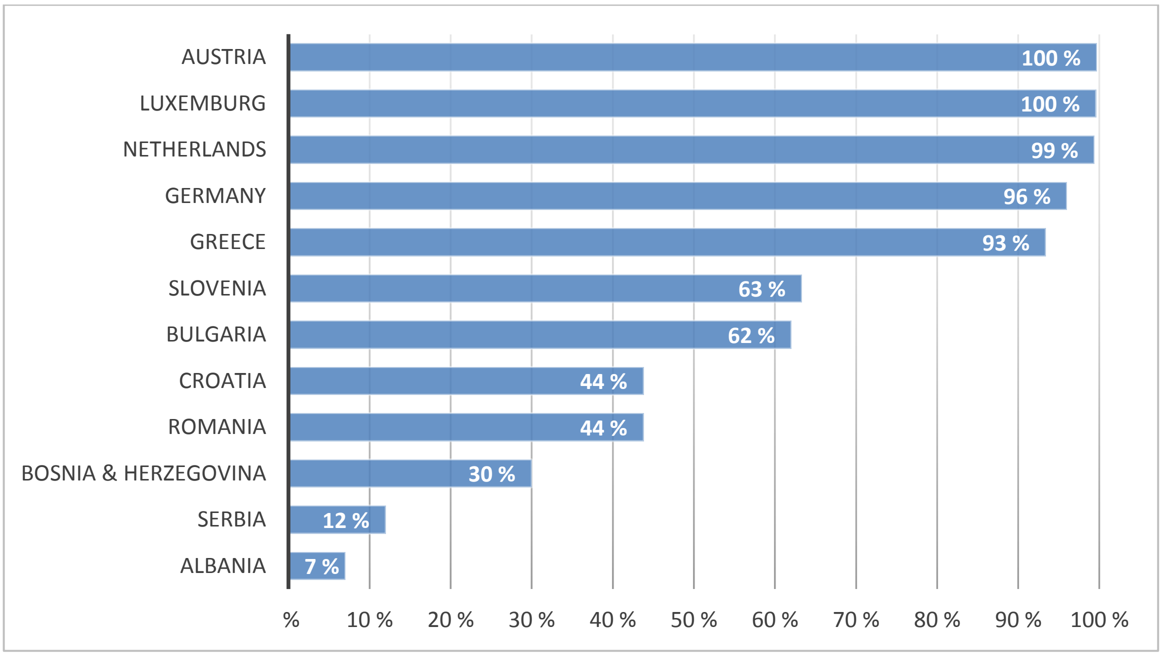


Fig. 2.8: Proportion of populations connected to WWTP with at least secondary treatment in select European countries, 2016.

Source: (moderate Eurostat, 2020)

Sewage sludge management also differs significantly among European countries. In compliance with EU policy, according to available Eurostat data for 2016, landfilling of sewage sludge has been totally abandoned or is phasing out in most EU Member States. There are some exceptions with very high sewage sludge disposal rate, however, such as Malta (100%; 2016) and Romania (74%; 2016). By contrast, in SEE, landfilling of sewage sludge is the prevailing solution, as shown in Fig. 2.9. Note that in Serbia and Bosnia and Herzegovina, nearly the entire quantity of generated sewage sludge is landfilled, as well as significant amount in Croatia (79%; 2016). Greece as well still considerably relies on sewage sludge disposal, where ca. one-third of generated sludge were landfills (2016). Slovenia, on the other hand, has almost completely eliminated landfilling, (1%; 2016), followed by Bulgaria (13%;2016) in SEE countries.

Sewage sludge application as fertilizer is the main management option in Ireland (81%; 2016), Norway (58%; 2016), France (44%; 2016) and Czech Republic (48%;

2016). In SEE, after landfilling, sludge application in agriculture is the second-most applied management option. Roughly half of sewage sludge is used as fertilizer in Albania (45%; 2016) and Bulgaria (56%; 2016). Composting is the main practice in Estonia (84%; 2016) and Hungary (59%; 2016), while Lithuania and Slovakia compost ca. half (both 47%; 2016). Interestingly, compositing is hardly practiced in SEE, accounting for only small percentages in Croatia (11%; 2016), Bulgaria (7%; 2016) and Albania (3%; 2016) (Fig. 2.9). In the most economically prosperous EU countries, incineration of sewage sludge is high, reaching up to 98% in the Netherlands (2016), 64% in Germany (2016) and about 50% in Slovenia and Austria (2016). This approach prevails in the old EU Member States due to concerns over pollutant release (heavy metals and micro pollutants) into soil, plants and groundwater, as well as those states' high population density and lack of available space for other options (Christodoulou and Stamatelatou, 2016). Only the most prosperous SEE countries apply incineration as a sludge management option: Slovenia (49%; 2016) and Greece (32%; 2016) (Fig. 2.9).

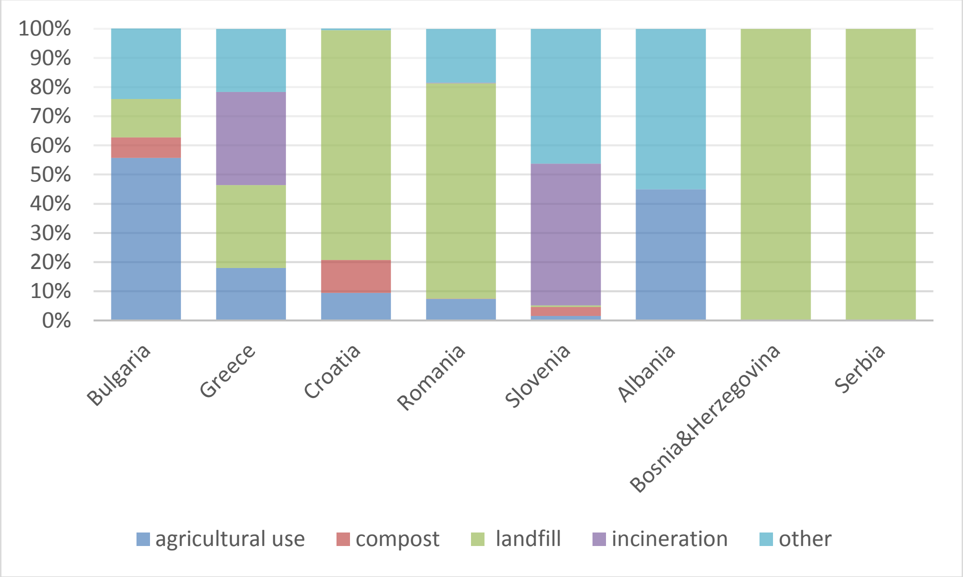


Fig. 2.9: Sewage sludge management from urban wastewater treatment in SEE, 2016.

Source: (moderate from Eurostat, 2020)

2.2.2 Waste Management

Based on 2016 Eurostat data, the average municipal solid waste (MSW) generation in the EU-27 was 488 kg/(cap*a). Of the total, roughly one-fourth of MSW is disposed in landfills, one-third is incinerated, another one-third recycled, and the rest composed and digested (Eurostat, 2020). As with the wastewater sector, there are considerable differences between European states regarding their municipal waste generation rates (Fig. 2.10) and management practice (Fig 2.11). If we compare Fig. 2.7, Fig. 2.10 and Fig 2.11, it is obvious that the economic strength of the country and its living standards primarily reflects both municipal waste generation rates and management practices. The most prosperous European countries, mainly those in northern and central Europe (Fig. 2.7) including Scandinavian countries and Switzerland, have the highest waste generation rates (Fig. 2.10) and, at the same time, the lowest disposal (landfill) rates (Fig 2.11). At first glance, near-zero disposal rates appear positive; however, these countries also incinerate the highest share of MSW (over 50%; 2016) (Fig 2.11), and in this way achieve their low disposal rates.

The least economically strong and transition European countries, mainly those in SEE, have both the lowest generation rates and the highest landfilling rates. Based on Eurostat data, average MSW generation rate in SEE in 2016 was 387 kg/(cap*a), 20% lower than the EU-27 average of 488 kg/(cap*a). At the same time, 75% of MSW in SEE is disposed ion landfills, significantly higher than the EU-27 average of ca. 25%. Greece has the highest MSW generation rate in the SEE with ca. 500 kg /cap*a, with 82% of waste being disposed in landfills. Similar trends are present in Bulgaria and Croatia with waste generation rate ca. 400 kg/cap*a (2016) in both, and disposal rates of 64% for Bulgaria and 78% for Croatia (2016). Exceptionally, Slovenia, although having the second-highest waste generation rate (457 kg /(cap*a), 2016) in SEE, has the lowest disposal rate (10%, 2016). Romania has the lowest waste generation rate in SEE (261 kg/(cap*a); 2016) and the highest disposal rate (70%, 2016). Albania, which is not an EU Member State, has the third highest generation rate in SEE (452 kg/(cap*a); 2016), as well as a high disposal rate (70%; 2016). Serbia, the focus of the case study in this research, has a generation rate of 268 kg /cap*a (2016) and landfilling rate of essentially 100% (2016).

Germany, Austria, and the Netherlands illustrate positive examples of the transition towards Circular Economy. These countries have lower MSW generation rates compared to northern countries, similar disposal rates, but higher recycling rates, with the best performance by Germany, reaching 50% (2016). It is important to note that recycling rate increases have been driven largely by material flows such as glass and paper, while bio-waste recycling lags significantly behind (EP, 2017). Although the Landfill Directive establishes targets for reducing biodegradable municipal waste (35% of 1995 levels by 2016, or 2020 for some countries), it does not advise specific treatment options. Bio-recycling (composting and anaerobic digestion) provides numerous advantages, such as reduction of greenhouse gases emissions; production of compost and/or soil conditioner which enhance soil quality; and potentially production of biogas, which increases energy independence and reduces fossil fuel dependence. Austria and Netherlands have the highest bio-recycling rates with ca. 30% (2016).

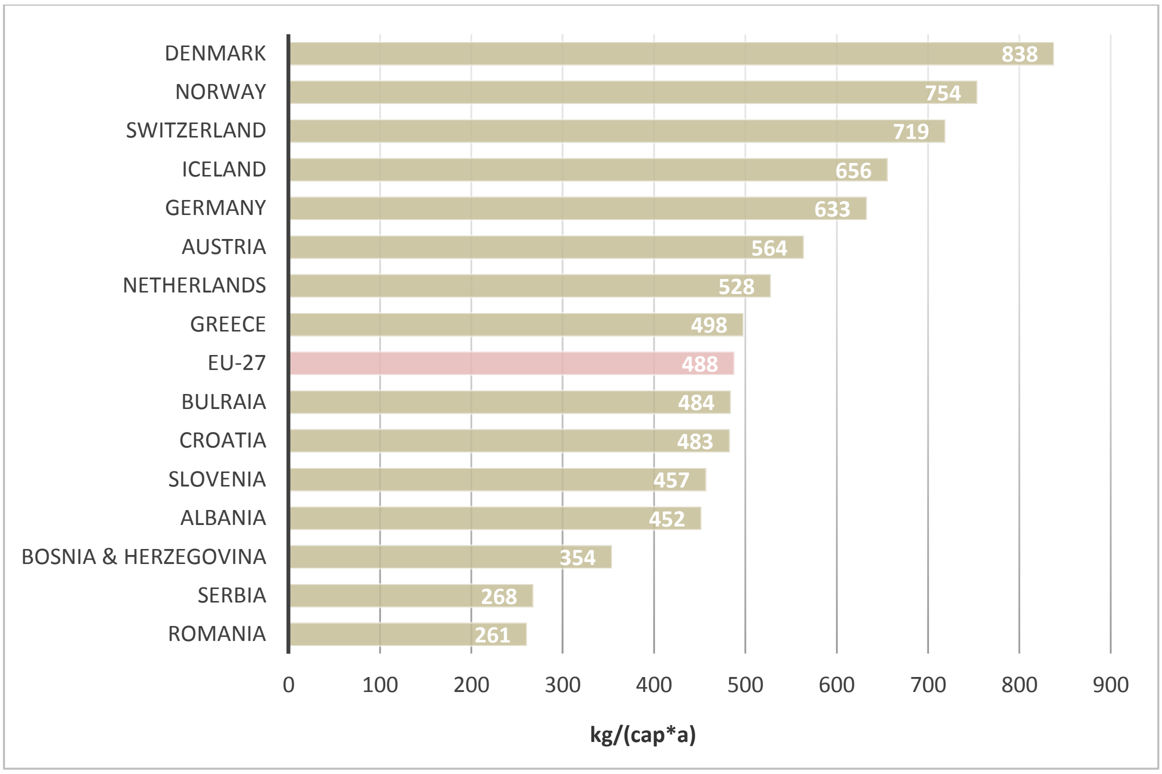


Fig. 2.10: Municipal waste generation per capita in selected European Countries and EU-27 in 2016.

Source: (moderate from Eurostat, 2020)

As Fig 2.11 illustrates that incineration is greatly practiced in the Nordic countries (Sweden, Norway, Estonia and Denmark) with incineration rates of over 50%, and Benelux countries approaching the same (ca.45%; 2016). Mediterranean countries, including Malta, Greece, Cyprus and Croatia do not utilize incineration as a MSW treatment option, while also achieving very low recycling rates of less 20%, even lower bio-recycling rates of just ca. 2-3% (2016).

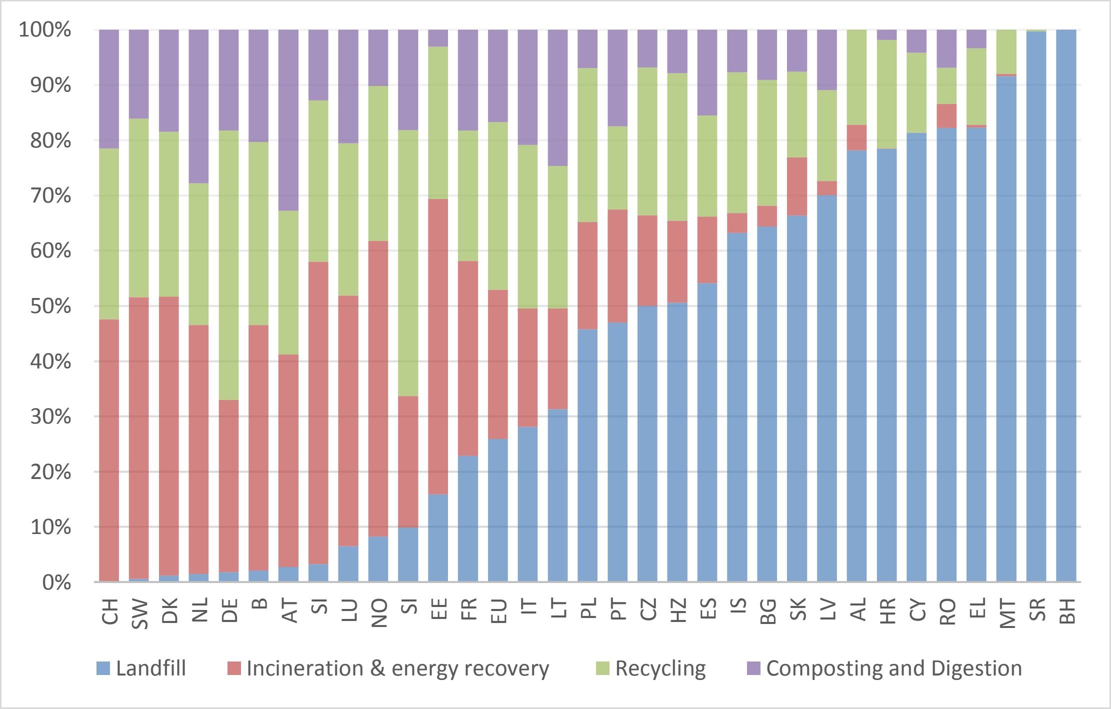


Fig 2.11: Municipal waste management practices in Europe, 2016.

Source: (moderate from Eurostat, 2020)

2.3 Opportunities for Integrated Resource Management

2.3.1 Wastewater Treatment Technologies

Convectional sanitation practices follow that municipal wastewater is collected in a sewer system and then evacuated to a WWTP. Through mechanical, chemical and biological processes, pollutants are degraded and eliminated in the WWTP, resulting in a purified, environmentally safe effluent that is discharged to the natural water cycle. Fig. 2.12 presents a general layout of a typical activated sludge process (ASP) WWTP.

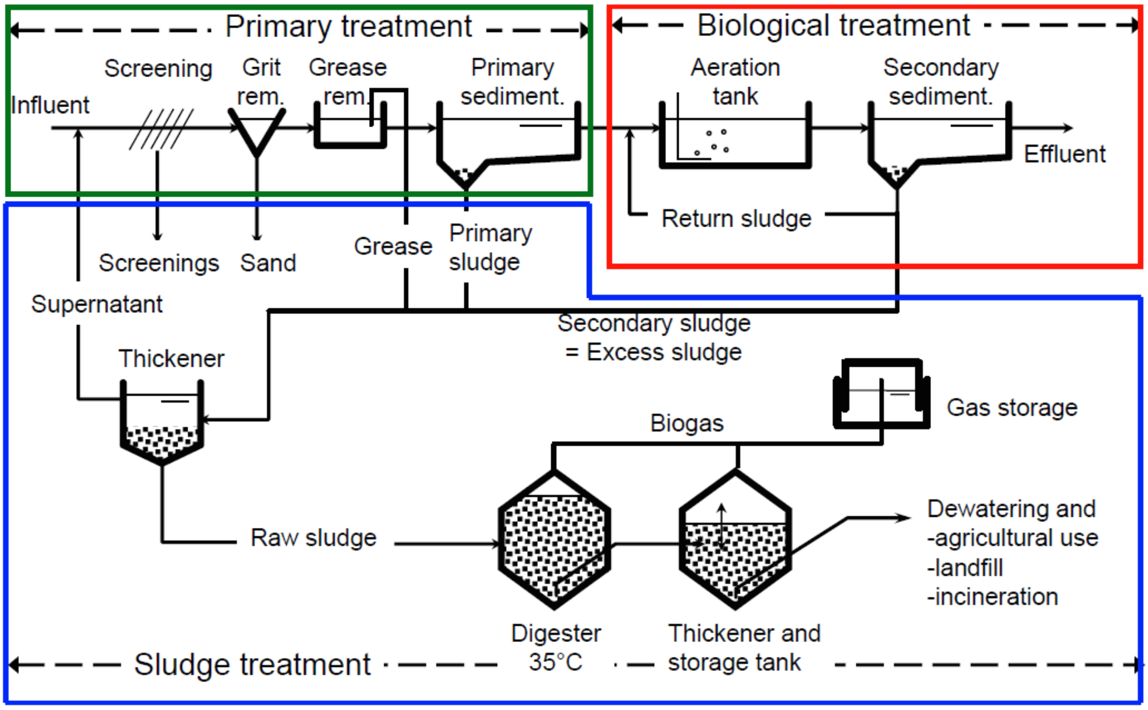


Fig. 2.12: General layout of WWTP based on activated sludge process.

Source: (Adopted Gujer, 2007)

In a traditional ASP, the preliminary treatment removes settable solids; this is followed by primary treatment, where raw wastewater is subsequently filtered through coarse and fine screens; then aerated in grit chambers with grease traps; and lastly deposited in sedimentation tanks where “primary sludge” is formed. Primary sludge has high organic content, and it is easily degradable. In secondary treatment (biological stage), the wastewater proceeds through an aeration tank in which carbon, nitrogen and phosphorus are removed, and ends in a secondary sedimentation tank. Nitrogen is removed through denitrification and nitrification processes. Phosphorus can be removed either by accumulation in biomass (enhanced biological phosphorus removal); by chemical precipitation in the form of barely soluble phosphates (normally as iron or aluminum phosphate); or by a combination of both processes. The settled biomass forms “activated sludge”, one part of which is returned to the aeration tank (“return sludge”) to continue biodegrading incoming wastewater, while the balance becomes “secondary” or “excess sludge”. Primary and secondary sludge are combined as activated sludge, which is thickened and then stabilized.

Anaerobic digestion is state-of-the-art technology for sludge stabilization, commonly used in many WWTPs worldwide (Iacividou et al., 2012). The anaerobic digestion process decomposes organic matter into final products of biogas and digestate. Biogas can subsequently be converted into thermal and electrical energy by a “co-generation” process. Digestate can be processed to recover phosphorus and the rest slurry, depending on regulation, can be applied as fertiliser, soil conditioner or composed, incinerated or landfilled. Although still practiced on the EU level (see Chapter 2.2.1), applying sewage sludge on agricultural land is slowly phasing out due to possible contamination with heavy metals, pathogens, pharmaceuticals and other persistent organic pollutants (Fijalkowski et al., 2017). This is particularly a concern if “indirect discharges” such as industry discharges are connected to the WWTP, since the type and quantity of hazardous substances is nearly impossible to control. In practice, most European countries and regions have now banned the application of sewage sludge as fertilizer.

Besides centralised WWTP, decentralised wastewater treatment technologies have been gaining on its significance and practical application for small-to-medium sized remote settlements. In that case long-distance wastewater evaluation is avoided while as system gains on flexibility.

A sequencing batch reactor (SBR) is a decentralized conventional wastewater treatment technology similar to ASP. The difference being that the SBR utilizes just a single vessel where all treatment steps occur sequentially in a cycle mode. This defining feature makes the process highly flexible, because the time of each stage can be varied depending on treatment requirements. Furthermore, the construction of a single reactor vessel is typically less expensive than constructing multiple reactors. For small-to-medium sized settlements with space limitations, SBR is appropriate technology. The duration of anaerobic, anoxic and aerobic stages can be controlled based on composition and treatment goals, allowing for improved process adaptability. Biological treatment, as well as chemical phosphorous removal, or a combination thereof, can be readily integrated.

Another example of the decentralized wastewater treatment is by constructed wetlands (CW) systems are artificial wastewater treatment systems which operate by the principle of natural wetland systems. CW are being effectively used for domestic wastewater treatment in smaller communities can effectively serve up to 1,000 PE (DWAa,2006). The CW systems exceeding this capacity requiring multiple modules in parallel. Wastewater applied to the reed bed trickles through the bed, where it is filtered and cleaned by microorganisms living in the root systems and bed litter. These microorganisms utilize the wastewater nutrients for growth, thereby digesting the nutrients and purifying the water. From a biological perspective, reed beds operate on the same principles as conventional WWTPs, the primary difference being that conventional systems rely on mechanical aeration. For the removal of suspended solids and large colloidal particles physical mechanisms like flocculation, settling and filtration play an important role (EPA, 2000). The plants themselves are not directly involved in the purification process, but rather they absorb oxygen from the air and release it through their root zone, or rhizosphere. This process supports large populations of aerobic microorganisms, which thrive in oxygen-rich environments, while anaerobic microorganisms congregate away from the root zones. In Europe, subsurface systems with the horizontal or vertical flow are often used for small decentralized treatment, offering high BOD treatment efficiency. Purification rates for organic substances is around 95% can be achieved (Lüderitz et al., 2001). Phosphorus removal often remains poor and shows extreme variation from nearly no elimination up to nearly 40% (DWA, 2006a).

Depending on pollutant concentrations in municipal wastewater (combined domestic and industrial wastewater), it is characterized as weak, medium or strong polluted. Tab. 2.1 summarises the limits of typical raw municipal wastewater, on which the weak, medium and strong characterizations are based. “Weak” municipal wastewater refers to diluted wastewater flow, including raw wastewater mixed with storm water (i.e., evacuated by a combined sewer system); wastewater from areas with high water consumption rate; and/or wastewater with high infiltration rates. “Strong” wastewater is concentrated wastewater generated from low water consumption and/or minimal infiltration (Henze, 2008).

Tab. 2.1: Typical composition of raw municipal wastewater, per pollutant concertation (mg/l).
Source: (Adopted from Henze, 2008 and Tchobanoglous, 2003)

Parameter / Wastewater Strength	Weak	Medium	Strong
Total Solids (TS)	390	720	1230
Total Suspended Solids (TSS)	250	400	600
Biological Oxygen Demand (BOD_5)	230	350	560
Chemical Oxygen Demand (COD)	500	750	1200
Total Nitrogen (N_{tot})	30	60	100
Ammonium-Nitrogen (NH_4-N)	20	45	75
Orthophosphate - Phosphorus (PO_4-P)	4	10	15
Total Phosphorus (P_{tot})	6	15	25

In cases where untreated or partially treated industrial wastewater is mixed with the domestic wastewater, certain pollutant concentrations may alter municipal wastewater composition. Industrial wastewater composition depends on the industry, production scheme, size, and other factors. In the case of industries involved in organic production (e.g., dairy, food, beverage) effluent is likely to contain higher concentrations of biological oxygen demand (BOD) and chemical oxygen demand (COD). An overview of literature values for some typical organic production wastewaters is summarized in Tab. *2.2*. In other industries, additional constituents such as heavy metals, phenols, oil and grease are also likely. Therefore, pre-treatment of industrial wastewater prior to combining with domestic wastewater is necessary to diminish potential corrosion of the sewer system, as well as to prevent adverse effects on the WWTP performance.

Tab. 2.2: Industrial wastewater pollutant concentration (mg/l) per industry type.
Source: (Adopted from Thomas and Pouet, 2004; Henze, 2008 and Gray, 2005)

Parameter	Agro-food	Dairy	Farms	Slaughterhouse	Pulp and Paper
TSS	30 - 700	200 - 400	1,500 - 3,000	800	100 - 2,500
BOD	100 - 7,000	850 - 2,250	1,000 - 2,000	400 - 2,500	25 - 15,000
COD	10 - 10,000	17,000			500 - 100,000

From a recovery point of view, wastewater is an interesting medium, as it is a carrier of energy (Tab. 2.3) and nutrients (Tab. 2.4). As seen in Tab. 2.3, wastewater is a carrier of potential, chemical, and most significantly, thermal energy from hot water consumption (e.g., showers, washing machines and dishwashers). From a recovery perspective, the most significant disadvantage to thermal energy recovery is the necessity for recovery to be close in proximity to the origin (to minimise heat loss). The chemically bounded energy stored in wastewater is typically much lower in comparison to thermal energy (Tab. 2.3) but can be transported long distances, making it more interesting to consider for recovery. The potential of chemically bounded energy recovery depends on the COD load in the wastewater. The potential energy in wastewater is extremely low (Tab. 2.3) and its reclamation may be practical only in cases involving high elevations (e.g., skyscrapers or respective topographies). In the scope of this research only chemically bounded energy is of interest.

Tab. 2.3: Theoretical energy content of wastewater per capita and annum. Source: (Adopted from Cornel et al., 2011)

Energy	Theoretical energy content
Potential Energy	6,1 kWh/(Cap*a)
Thermal Energy	254 kWh/(Cap*a)
Chemical Energy	152 kWh/(Cap*a)
Total	412 kWh/(Cap*a)

As seen in Tab. 2.4 below, wastewater acts as a carrier of the nutrients essential for agricultural production, namely nitrogen (N), phosphorus (P) and potassium (K). N and P are pollutants whose removal is important for the ecosystem preservation point of view while as K remains less interesting due to its non-harmful effect on the ecosystems. Nitrogen is the key element for fertilizer production. Even though nitrogen has the highest volume of all gases in the atmosphere with ca. 78 vo.% N_2, its usage for fertilizer production, for example, via the Harber–Bosch process, is energy intensive, requiring 9-13 kWh/kg NH_3-N (Cornel et al, 2011); nitrogen recovery from wastewater is thus interesting from an energy perspective. Nitrogen occurs in wastewater primarily from urine; each person on average contributes 11-13 g/day (DWA, 2008). During the wastewater treatment process up to one third of nitrogen may become physiologically bounded in activated sludge, the balancing remaining in the wastewater as ammonium ion and is nitrified/denitrified, requiring an energy demand of 1.5 – 2.9 kWh/kg N (Cornel et al, 2011). The nitrogen recovered from wastewater could meet 14-20% of the requirement for chemical fertilizers (Cornel et al, 2011).

Tab. 2.4: Annual loads of nutrients in municipal wastewater and their shares in wastewater streams.
Source: (Cornel et al., 2011)

	Wastewater	Greywater	Urine	Faeces
Compound	kg /(Cap*a)	%	%	%
N	4-5	3	87	10
P	0.75	10	50	40
K	1.8	34	54	12
COD	30	41	12	47

Phosphorus occurs in urine and faeces with, each person per day contributing 1,8 g P/(Cap*day) (DWA, 2008). Through WWTP secondary treatment around 40% is of Phosphorus is removed with primary and secondary sludge. Another 50% is removed in the tertiary treatment step by physio-chemical or biological phosphorus removal. Thus, 90% of input phosphorus is bounded into sewage sludge in a modern WWTP (Cornel and Schaum, 2009).

2.3.2 Waste Treatment Technologies

MSW is managed in vastly different ways worldwide. First, as seen in Fig. 2.13, MSW can be collected either as “source-separated” or as “mixed” waste, after which various separation and treatment processes are applied. Source separation is important with respect to the waste hierarchy and Circular Economy principles. As shown in Fig. 2.10 and further elaborated in Chapter 2.2.2, landfilling is still used extensively as a waste management option by many European countries. While central and northern European countries tend to rely heavily on incineration those in the south and east rely primarily on landfills (Fig. 2.10). When landfilled, bio-waste undergoes anaerobic degradation, releasing greenhouse gases (GHGs) and liquid leachate.

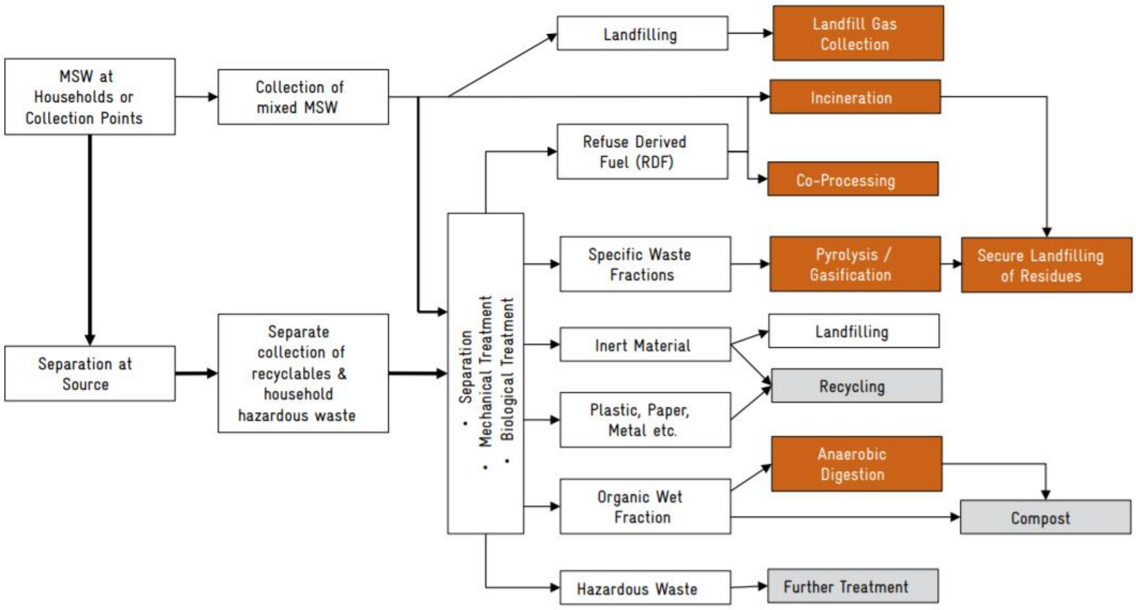


Fig. 2.13: Overview of MSW material flows, with utilization and treatment options.

Source: (GIZ, 2017)

Waste-to-energy processes can play a role in the transition to Circular Economy, provided that the EU waste hierarchy (Fig. 2.6) is appropriately applied and that choices made do not prevent the higher levels of prevention, reuse and recycling. Here, primary waste selection practices have improved recovery and reuse rates. As an alternative technology to treat mixed MSW, mechanical biological treatment (MBT) and production of refuse-derived fuels (Fig. 2.13) have been applied in the new EU Member States. Although MBT technology application helps meet Landfill Directive targets, it is less than optimal in achieving recycling and reuse targets, as MBT-treated waste flows are of lower quality as compared to primary selection. The remaining challenge is developing regulated markets for alternative fuels that are the outputs of MBT technology. It may thus be the case that MBT is best viewed as a temporary solution toward Circular Economy. Nevertheless, in 2017 the European Parliament reported that MBT application may discourage citizens from participating in source separation if they know that MBT is applied. The EP in its Study “Towards a Circular Economy – Waste Management in the EU” states that MBT “is characterised as a disposal option, instead as one to gain high-quality inputs for the Circular Economy” (EP, 2017b). Therefore source separation of MSW is the best management option as it allows full potential recovery, while principles of CE are respected.

Circular Economy promotes environmentally sound waste management, leading to better environmental protection, reduced climate change effects, and improved resource efficiency, made possible through the waste hierarchy (Fig. 2.6), which emphasizes waste avoidance and recycling over end-of-life treatment options. To support the transition to Circular Economy, the Commission recommends separate collection schemes for biodegradable waste, increased recycling quotas, and reduced incineration and landfilling.

2.3.3 Technologies for Resources Recovery

2.3.3.1 Energy Recovery

One of the core principles of Circular Economy is to maximize nutrient cycles and foster effective, sustainable resource management (Vaneeckhaute et al., 2017). The increasing demand for alternative energy, combined with landfill diversion of organic waste, endorse the adoption of the anaerobic digestion process. The UN and European Commission (EC) recently designated integrated treatment of sewage sludge, organic waste and agricultural residues through anaerobic digestion (i.e. co-digestion) as an environmentally friendly, nutrient- and energy-efficient management practice (EU, 2011).

Anaerobic digestion is a biological process performed in an oxygen-free environment in which organic matter is degraded in a series of metabolic interactions with different microbes. There are three effective temperature ranges where anaerobic digestion takes place (Evans, 2001): Cryptophilic: $t < 20°C$; Mesophilic: $20°C < t < 45°C$; and Thermophilic: $t > 45°C$. Each temperature range is suitable for a specific bacteria group; thus, it is important that the temperature within the reactor remain constant. Each of the three digestion types has advantages and disadvantages. Mesophilic digestion is widely applied globally, being a more flexible and tolerant process than the Thermophilic process; but it also nets lower biogas production and requires a large digester. Thermophilic digestion requires shorter degradation time than Mesophilic, plus has higher biogas yields and better removal of pathogens and viruses, but is more expensive technology, requires higher energy inputs, and is more difficult to monitor and control. Cryptophilic digestion is appropriate for use only in certain tropical and subtropical locales.

Anaerobic digestion can be divided into four main stages (Fig. 2.14). In the first step, “hydrolysis”, complex organics are solubilised by the extracellular enzymes of hydrolytic fermentative bacteria into smaller molecules. Fats are decomposed into long chain volatile fatty acids (VFA) and glycerol by the lipase enzyme; proteins are converted into amino acids by the enzyme, protease; and carbohydrates are broken into simple sugars by the enzymes cellulose, cellobiase, xylanase and amylase (Kaseng at al., 1992).

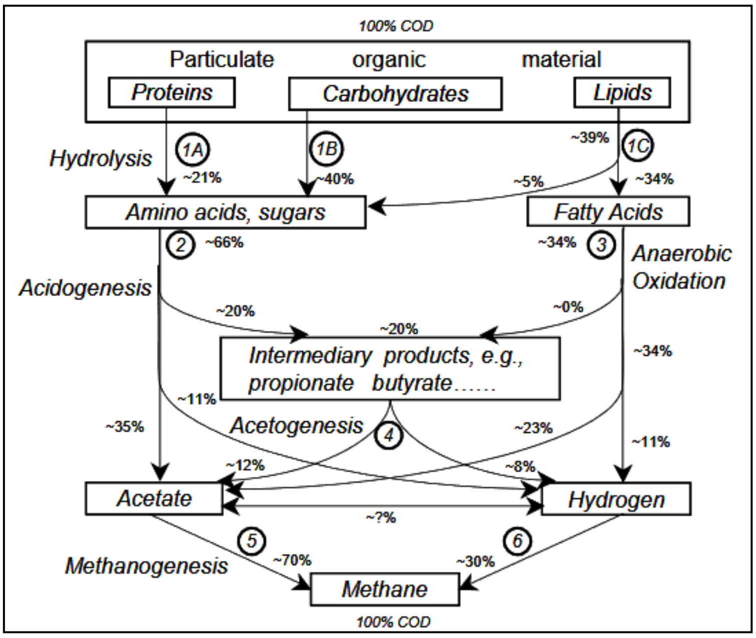


Fig. 2.14: Anaerobic digestion process scheme.

Source: (Lu and Ahring, 2007)

The second step in the anaerobic digestion process is “acidogenesis”, in which acidogenic bacteria convert the products of hydrolysis into simpler organic compounds. The final products of acidogenesis consist of roughly 51% acetate, 19% hydrogen gas, and alcohols or lactate (Angelidaki *at al*., 2002). Acetic acid is produced from the monomers, while VFA forms from proteins, fat, and carbohydrates produced in the previous stage. VFA consists mainly of acetic, lactic and propionic acid (Evans, 2001)**,** decreasing the pH level. If the pH drops below 5.0, ethanol production will increase (Ren *at al*., 1997), and if pH continuous to drop to below 4.0, all acidogenic processes could terminate (Hwang *at al*., 2004). The specific by-products formed during this stage depend on the composition of the input material into the reactor, as well as on the reaction temperature and pH (Buekens, 2005).

“Acetogenesis” is the third stage of anaerobic digestion, in which decomposition of VFAs longer than two carbon atoms and alcohols longer than one carbon atom which cannot be used by methane-producing bacteria, are converted to acetate (CH_3COOH), carbon dioxide (CO_2) and hydrogen (H_2).

The fourth and final step of anaerobic digestion is “methanogenesis”, in which methane and carbon dioxide are produced from products of the previous step: acetic acid, acetate, methanol, carbon dioxide and hydrogen (Evans, 2001). Up to 70% of the total methane production originates from acetate (Klass, 1984).

The following chemical equations show various products, by-products and intermediates created in stages of anaerobic digestion, and their conversion into methane and carbon dioxide.

(1) $CH_3COOH \longrightarrow CH_4 + CO_2$

(2) $CH_3OH + H_2 \longrightarrow CH_4 + CO_2$

(3) $CO_2 + 4H_2 \longrightarrow CH_4 + CO_2$

“Anaerobic co-digestion” (AcoD) is defined as the joint anaerobic treatment of sewage sludge as a base substrate, combined with other organic flows (Rosenwinkel et al., 2015). These “other organic flows” may be from industry, commerce, agriculture or municipal solid waste. Typically, existing WWTP digesters are designed with 15-30% surplus capacity (Mattioli et al., 2017). The aims of AcoD are to improve digestate quality (Cabbai, 2016) and increase biogas yield, thereby maximizing positive environmental and financial benefits (Long et al., 2017). AcoD has been practiced in Europe for more than 20 years, with Germany and Sweden generally pioneering the efforts (Iacovidou et al., 2012). Nghiem et al. (2017) argues that full-scale anaerobic co-digestion installations are associated with policies fostering waste to energy; thus, full-scale co-digestion projects are operational in only a few countries (Tab. 2.6).

The biggest advantage of AcoD is its potential to utilise substrates, which are otherwise difficult to mono-digest due to nutrient imbalances, rapid decomposition and presence of inhibitors (Holliger et al., 2017). Aside from the overall aim to increase energy yield, AcoD has other advantages, including stabilized digestion process due to optimised nutrient balance; GHG reduction; and economic gains from sharing infrastructure and associated costs (Hagos et al., 2017). Even though there is a vast array of potential mixing substrates, the digester should not be misused as a "universal-waste bin", and in that respect Rosenwinkel et al. (2015) advise mixing up to three diverse co-substrates, with co-digestion proportion in the range 5-20% (Maktabifard et al., 2018). There is a broad range of co-substrates suitable for AcoD, including fats, oil and grease (FOG); food waste; organic municipal solid waste; food/beverage processing waste (e.g., brewery, dairy); energy crops; agricultural residues; livestock manure; biofuel by-products (e.g., corn-ethanol stillage, crude glycerol, spent microalgae); and other high concentration waste (Shen et al, 2015). According to Rosenwinkel et al. (2015), there are five main pre-conditions for substrate suitability for co-digestion: i) substrate availability; ii) volume reduction potential; iii) feasibility to mix with raw sewage sludge; iv) pump-ability; and v) free of interference and harmful substances.

One of the main constraints for AcoD process stability is the unbalanced macro-nutrient (C/N ratio) content. Mixing nitrogen rich substrates (low C/N ratio) with carbon-rich (high C/N ratio) substrates is important for process stability and optimizes biogas production (Hagos et al., 2017). Sewage sludge is mainly characterised with a low C/N ratio, ranging from 6 to 9 (Iacovidou et al., 2012) and high buffer capacity (Mata-Alvarez et al, 2014). Therefore, suitable co-substrates for AcoD with sewage sludge include those rich in easily degradable carbon, with limited nitrogen content (high C/N Ratio). In addition, it is important to avoid additional nutrient loading through the filtrate water. Thus, substrates such as food waste are particularly suitable for co-digestion and biogas yield (Björn et al., 2017). For example, nitrogen and phosphorus content in food waste is typically 1 kg N/t and 0.25 kg P/t waste, respectively (Bolzonella et al., 2018), while the waste also has more readily biodegradable carbon (Koch et al., 2016), and a C/N ratio of 15-32 (Hagos et al., 2017); these properties make food waste highly suitable for co-digestion. Food waste also provides additional carbon, which improves digestion performance through reaction kinetics (Iacovidou et al., 2012).

Manure, on the other hand, has especially high nutrient content (low C/N ratio), and nitrogen content ranging from 5 kg N/t (C/N ratio 16-25) for cattle manure to 15 kg N/t (C/N ratio16-25) for chicken manure (Bolzonella et al., 2018, Hagos et al., 2017). Therefore, manure combined with sewage sludge is less suitable for AcoD than food waste. Therefore addition of manure as a co-digestion substrate should be limited to moderate.

Other suitable substrates include other types of organic waste, FOG, crop residues and organic outputs from industry (wastewater and solid organic waste). From an energy perspective, adding FOG as a co-substrate is interesting. FOG has an energy potential of 0,7-1,1 m^3 CH_4 /kg organic dry matter (oDM) and accounts for 25-40% of the total wastewater COD (Mata-Alvarez et al, 2014). FOG is also generally already available at WWTPs, having been prior removed in the primary treatment step. The application of FOGs must be limited to Organic Loading Rate (OLR) of 2,5 kg oDM/m^3 to avoid accumulation on VFAs, which inhibit the AcoD process (Mata-Alvarez et al, 2014). Crop resides have a relatively high C/N ratio (wheat straw 50-150, corn straw 50-56) and, as such, provide process stability (Hagos et al., 2017). Organic flows from industry (e.g., beverage production, milk and food processing) are particularly beneficial for co-digestion processes for several reasons, including high concentrated organic content, continuous and constant volume and mass flows, constant composition and homogeneity, and absence of harmful contaminates (Rosenwinkel et al., 2015).

If co-digestion is pursued, supplementary facilities must also be considered, such as for waste processing and storage, inert solids removal, off-gas treatment, sludge treatment, bio-solids drying, and enhanced biogas purification (Long et al., 2017). In the case of integrating co-digestion in an existing WWTP upgrade or re-adaptation, anti-clogging processes and associated storage, pumps and mixers are also necessary. All issues concerning digestion instability and inhibition should be carefully considered. Increased OLRs also increase gas production; and at certain limits, the process becomes unstable due to the formation of VFAs.

High variability of co-digestion feedstock composition and volume may further destabilise the AcoD process due to pH fluctuations caused by the rapid accumulation of VFAs in the digester. This may be alleviated by adopting a two stage anaerobic digestion process to separate hydrolysis/acidogenesis and methanogensis, which improves stability and increases methane production. Depending on the composition of the co-digestion feedstock, inhibitory substances may also be generated during digestion process, including ammonia (from protein-rich organic waste): long-chain fatty acids (from lipid-rich waste, such as FOG and food waste): and heavy metals (usually from industrial wastewater).

Digestate is the by-product of anaerobic digestion; its composition is variable depending on the input material, digester type and process parameters. There are, therefore, no standard composition values. Nevertheless, digestate properties are generally very suitable for nutrient assimilation by plants. Digestate is rich in effective organic carbon, important for humus building and thus beneficial for soil quality. Average carbon concertation in digestate is 33.7 kg C/t fresh weight (FW) which is almost double that of pig manure (Vaneeckhaute et al., 2017). The oDM content ranges from 30-80%, with higher oDM content associated with bio-waste as a co-substrate (Vaneeckhaute et al., 2017). The fertilising properties of digestate are dependent on N and P concertation. Animal waste slurry and crop residue improve digestate quality, as they are significantly higher in nutrient concertation than sewage sludge: 6.78 kg N/t FW and 5 kg P/t FW for pig slurry, compared to 0.1-1 kg N/tFW and 0.04-0.7 kg P/t FW (phosphorus precipitation) and up to 15 kg P/t FW (biological P removal) for sewage sludge (Vaneeckhaute et al., 2017).

2.3.3.2 Phosphorus Recovery

The situation described in Chapter 2.1.2 has stimulated initiatives to develop technologies to recover phosphorus from secondary sources, including municipal wastewater (Drenkova-Tuhtan et al., 2016). Phosphorus removal from wastewater is accomplished via biological and/or chemical processes, transferring the phosphorus from the dissolved phase into the sludge, and then recovering it through one or more different points in the WWTP by applying the appropriate diverse technologies.

Fig. 2.15 illustrates the possible phosphorus recovery points in the WWTP. Phosphorus may be recovered from one or more of several phases:

Aqueous Phase: Marked green and including separated urine flow (1), effluent (2), digester supernatant (3.2) or digested sludge in a digester (3.1);

Sewage Sludge Phase: Marked blue and including digestate (4.1), thickened digestate (4.2) and dewatered digestate (4.3); and

Sewage Sludge Ash Phase: Marked red and including sludge ash incineration (5).

If phosphorus is eliminated from the wastewater via enhanced biological removal or chemical precipitation, around 90% will end up in the sludge; thus, the greatest theoretical recovery potential is from the sludge or ash after incineration.

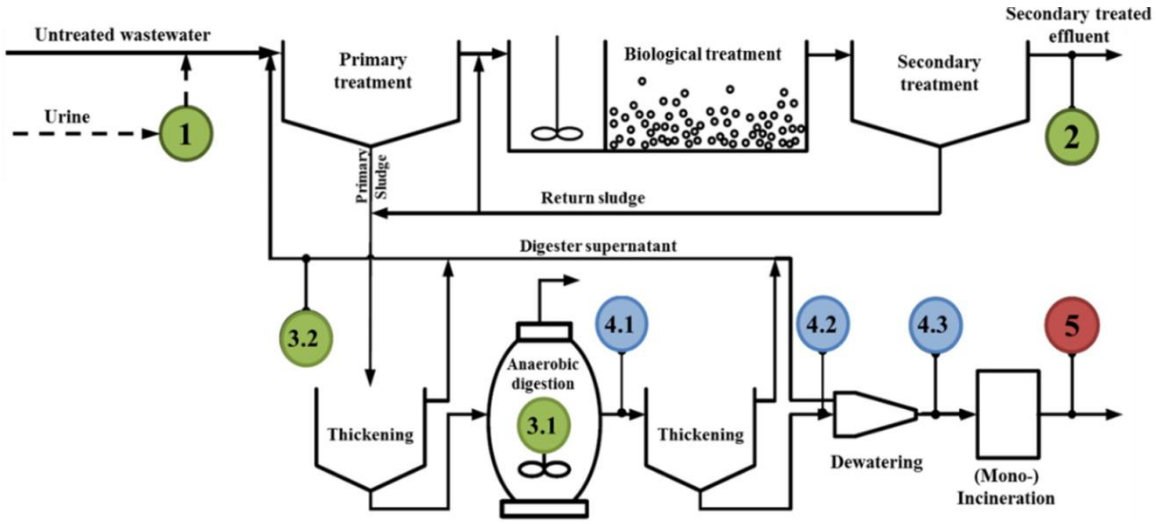
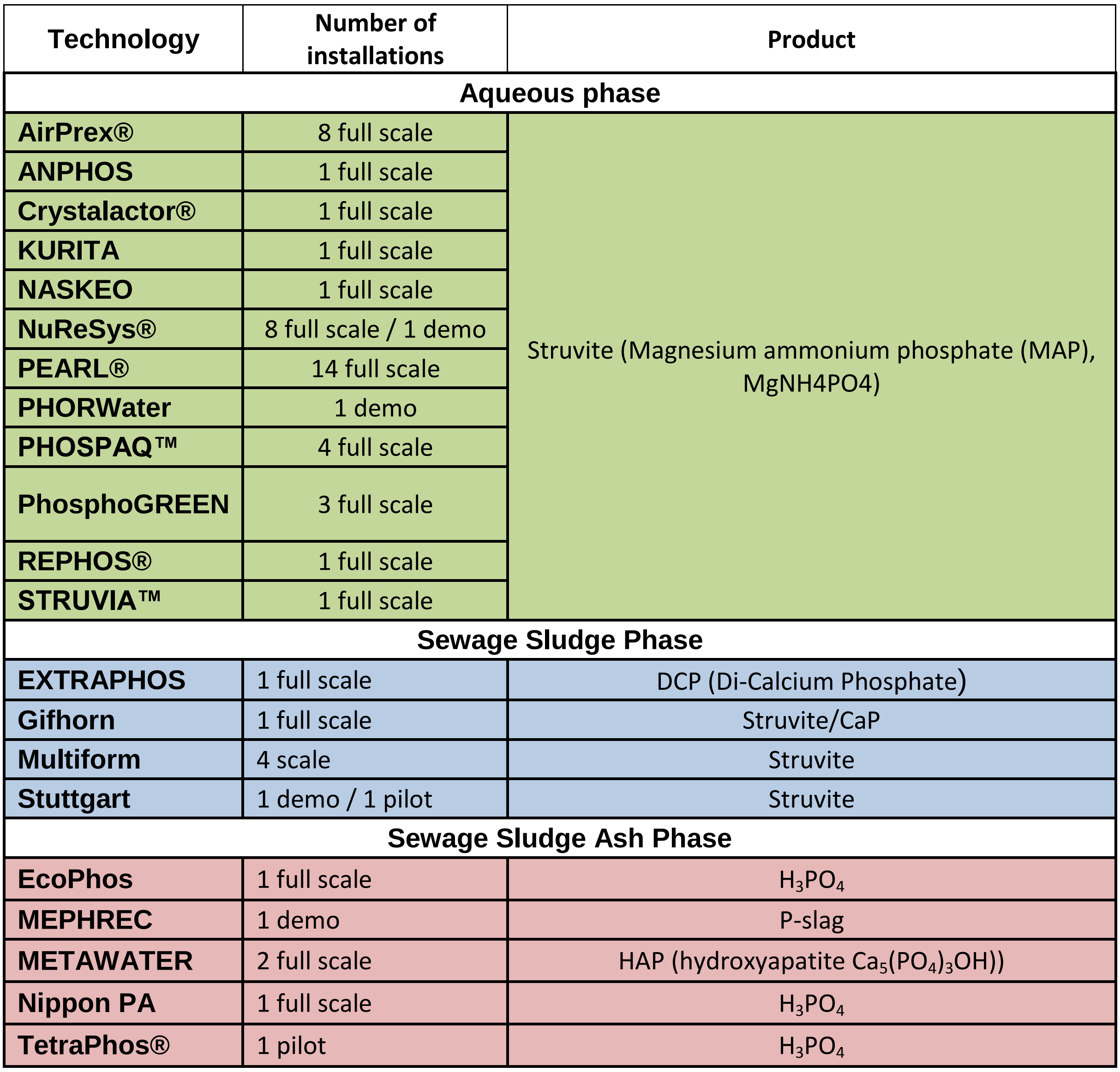


Fig. 2.15: Suitable locations for phosphorus recovery from municipal wastewater and sludge treatment: Aqueous (green); Sewage Sludge (blue); Sewage Sludge Ash (red). Source: (Adopted Egle et al., 2016; Montag, 2008)

There are more than 50 phosphorus recovery technologies (Egle et al., 2017) based on thermochemical and precipitation techniques and that seek to close the biogeochemical P cycle (Tonini et al., 2019). The most applied phosphorus recovery technologies worldwide are summarized in Fig. 2.16. Looking back at Fig. 2.15, and as Fig. 2.16 indicates, phosphorus is most often recovered from the aqueous phase (green) where the final product is “struvite”. On the EU level, it is projected that valorised phosphorus products may subsidise 17-31% of conventional P fertilizers by 2030 (Huygens et al., 2019, Tonini et al., 2019).



Technology	Number of installations	Product
Aqueous phase		
AirPrex®	8 full scale	Struvite (Magnesium ammonium phosphate (MAP), MgNH4PO4)
ANPHOS	1 full scale	
Crystalactor®	1 full scale	
KURITA	1 full scale	
NASKEO	1 full scale	
NuReSys®	8 full scale / 1 demo	
PEARL®	14 full scale	
PHORWater	1 demo	
PHOSPAQ™	4 full scale	
PhosphoGREEN	3 full scale	
REPHOS®	1 full scale	
STRUVIA™	1 full scale	
Sewage Sludge Phase		
EXTRAPHOS	1 full scale	DCP (Di-Calcium Phosphate)
Gifhorn	1 full scale	Struvite/CaP
Multiform	4 scale	Struvite
Stuttgart	1 demo / 1 pilot	Struvite
Sewage Sludge Ash Phase		
EcoPhos	1 full scale	H_3PO_4
MEPHREC	1 demo	P-slag
METAWATER	2 full scale	HAP (hydroxyapatite $Ca_5(PO_4)_3OH)$)
Nippon PA	1 full scale	H_3PO_4
TetraPhos®	1 pilot	H_3PO_4

Fig. 2.16: Overview of phosphorus recovery technologies, installations and product.
Source: (Adopted Kabbe, 2017; Egle et al., 2016)

Although phosphorus recovery from wastewater isn't yet common, due to policy changes as elaborated in Chapter 2.1.3 it will likely become increasingly important and practiced in the future. For instance, in Germany, a new Sewage Sludge Ordinance mandating phosphorus recovery in municipal WWTPs larger than 50,000 PE was introduced in 2017 (AbfKlärV, 2017). Plant operators must implement phosphorus recovery actions by 2029 for WWTP capacity greater than 100,000 PE and by 2032 for WWTPs between 60,000 and 100,000 PE, which affects around 500 WWTPs (BMU, 2017).

Fig. 2.17 shows future phosphorus recovery obligations and possible recovery methods. At least 50% of this phosphorus must be recovered at the WWTP, or its content must be reduced to below 20 gP/kg DM. If the sewage sludge is treated thermally, at least 80% of phosphorus contained in sewage sludge incineration ash must be recovered (AbfKlärV, 2017). The amount of sewage sludge that may be used in agriculture fertilizer may originate only from municipal WWTP and it is limited to 5 t DM/ha within a three-year period (AbfKlärV, 2017).

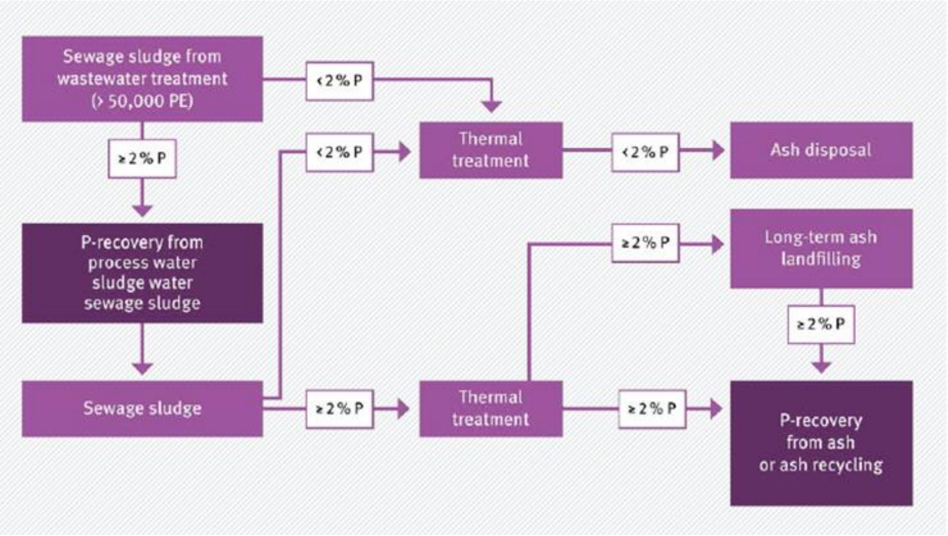


Fig. 2.17: Phosphorus recovery obligations set by the German Sewage Sludge Ordinance.

Source: (UBA, 2018)

On the European level, as explained previously in Section 2.1.2, the new EU Fertilizing Products Regulation (2019) will accelerate phosphorus recovery from waste flows, as it opens a European market for recycled fertilizers within harmonized quality standards. It should be noted that phosphorus recovery from sewage sludge can be integrated into existing WWTPs as an additional retrofit module, making the technology flexible and adaptable.

Studies have shown that MAP possesses good fertilizer quality (UBA, 2018; Massey et al., 2009; Römer, 2006). MAP can be produced from sludge water or sewage sludge via different processes, one being the Stuttgart process. In the Stuttgart process, MAP is produced from digested sludge with chemical phosphate precipitation of iron or aluminium salts. This gives this technique advantage as its respects the Waste hierarchy principle. Simplified, the Stuttgart process consists of two steps: first, acidic leaching of metal phosphates from anaerobically stabilized sewage sludge; followed by precipitation of MAP by addition of magnesium oxide adjusted with sodium hydroxide. Citric acid is added to complex the dissolved iron and heavy metals to prevent their transfer to the final product. Fig. 2.18 shows a schematic of the Stuttgart process based ony Meyer et.

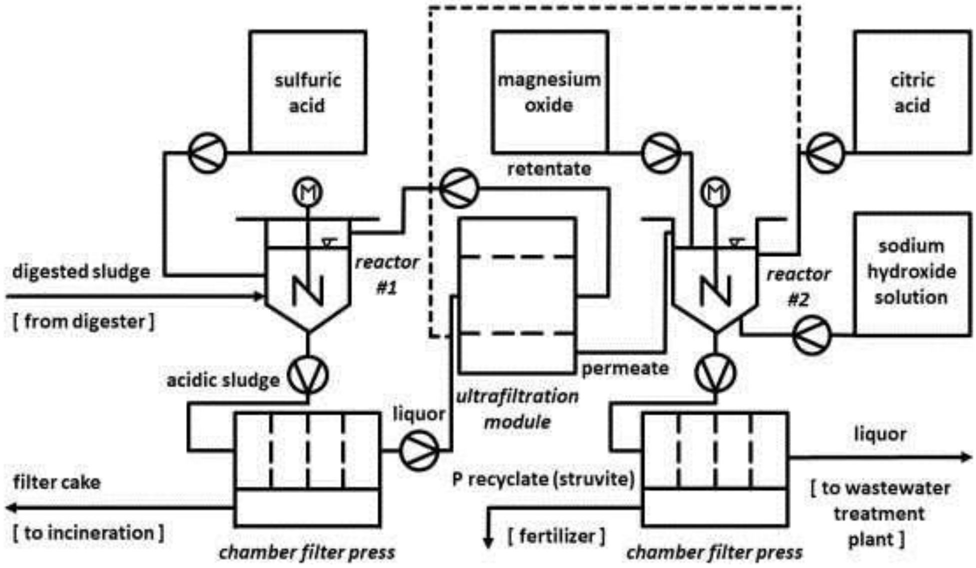


Fig. 2.18: Schematic of the Stuttgart Process.
Source: (Meyer et al., 2019)

As Fig. 2.18 shows, chemicals are necessary to drive the process, with consumption dependent on the sludge properties, the precipitant used, and the phosphorus recovery rate.

2.3.3.3 Wastewater Recovery

Re-use of wastewater can include irrigation of agricultural land, parks, sport fields and recreation, in-house use (e.g. toilet flushing) and industrial process water. Although conventional secondary wastewater treatment reduces pathogens to roughly one to three log units depending on technology, effluents still contain around 104-105 E.coli/100ml. Thus, all sanitation systems discharge potentially pathogenic microorganisms if no special disinfection step is completed. If treated wastewater is reused, safety and public health aspects must be considered. For pathogen reduction below 2,000 E.coli/100mL, further treatment by ultraviolet disinfection, ozone oxidation, membrane treatment or chlorination are needed. In order to re-use wastewater, different technologies are used, such as UV disinfection, chlorofocation, ozonation and membrane filters.

UV disinfection may be used as an add-on installation to existing wastewater treatment technologies. UV disinfection destroys bacteria in wastewater treatment effluent through exposure to ultraviolet radiation. The process is rapid and no hazardous by-products. The efficiency of the process depends on numerous factors related to effluent characteristics. Dissolved and suspended solids can decrease transmission, with the best performance achieved with TSS below 5 mg/L.However, regrowth of microorganisms can occur, especially if UV-disinfected water is stored for a long time or transported over long distances.

2.4 Bottlenecks to Implement Integrated Solutions

Integrated solutions may be a particularly promising strategy towards a Circular Economy. However, application of these integrated concepts will be challenging for countries with existing conventional wastewater and waste infrastructure. In some countries, the lack of infrastructure could be a driver for integrated solutions. As Chapter 2.2 presents, the economic power of European countries is reflected in the technologies they employ in their wastewater and waste management. SEE countries significantly lag central and northern European countries with respect to their environmental infrastructure. Only roughly half of SEE countries have access to, at a minimum, secondary wastewater treatment, while sewage sludge is predominantly disposed in landfills or applied as fertilizer (Fig. 2.8; Fig 2.9).

Based on Eurostat data for 2016, in the waste management sector, two-thirds of MSW is landfilled on average in SEE, five times more than the EU average. The diversion of waste and sewage sludge from landfills is increasingly important and may present an opportunity to implement viable integrated solutions. To achieve this, several actions are necessary: implement the primary waste selection program; optimize and modernize waste management infrastructure to collect and separate waste; and establish markets for secondary materials (EP, 2017b). As discussed in Chapter 2.1, the revised EU policy, notably Circular Economy Package (2018) and EU Fertilizer Regulation (2019), are important drivers along this path. Despite these drivers, integrated solutions remain underutilized due to certain constraints that hinder their wider application.

The barriers to adopting integrated solutions can be classified into four categories: financial, technical, social and legal, which are further subdivided (Tab. 2.7). Financing must be secured, as well as the expertise and buy-in of different stakeholders, for the system to function. Conventional thinking regarding separate waste and wastewater management must be overcome, and social acceptance and adoption of recycling must be sustained. There are also some limits imposed by current governance practices; for these, intra-organizational and intra-sectoral management of inter-organizational and inter-sectoral flows of materials and energy are necessary (Korhonen et al., 2018). This ultimately requires adopting EU policies into national legislation, as well as institutional collaboration on enforcement. The bottlenecks listed in the Tab. 2.5 are explained in more detail in the subsequent chapters.

Tab. 2.5: Bottlenecks hindering the implementation of integrated solutions. Source: (Adapted from Shen et al., 2015, Long et al., 2017 and Barquet et al., 2020)

Financial	Lack of available capital expenditures Uncertain payback period Lacking government incentives Low utility costs
Technical	Inadequate knowledge Quality of final product(s) Feedstock quantity and logistics Safety issues
Social	Social acceptance Informational barriers Inter-sectorial collaboration challenges Primary waste collection challenges
Legal	Regulatory uncertainty Discrepancies between governmental agencies

2.4.1 Financial Barriers

As listed in Tab. 2.5, financial barriers include lack of available capital expenditure, uncertain payback, lacking governmental incentives and low price of utility costs. To implement an integrated project, stakeholders must secure financing and make a feasible business case. If AcoD and nutrient recovery is to be integrated in the WWTP, a higher investment commitment is necessary, which in turn may hinder or prolong implementation. As AcoD and nutrient recovery processes are non-standard additions to a conventional WWTP, it may be considered risky for bank and donor financing, given potentially uncertain payback period depending on factors such as co-substrate feedstock availability and composition, markets, and potential co-revenue streams (e.g., generated energy, digestate and recovered minerals). In this respect, one of the main constraints is the still-developing market for recovered nutrients and uncertainties regarding their future price (Egle et al., 2016). As nutrient recovery technologies are still emerging, output prices are still not competitive with the low market price of conventional fertilizers (Barquet et al., 2020). However, increased technology application and resulting economies of scale, combined with anticipated price increases in conventional fertilizer due to shrinking phosphate rock reserves, may tip the balance toward integrated solutions.

Governmental incentives for recovered energy and nutrients are also important drivers toward integrated solutions. Germany has been supporting diverse renewable energy projects, including anaerobic digestion, by providing motivating feed-in tariffs and offering a stable legal framework. Similar incentives for recovering nutrients from waste flows would similarly accelerate adoption of these technologies. Finally, low utility collection fees (i.e., waste and wastewater fees) hinder realization of integrated projects, since it prolongs the investment payback period. Waste gate (i.e., landfill) fees are also important and should be substantial enough to accelerate the investment payback.

Thus, as a general rule, energy dependent countries with high energy prices are most suitable for adopting integrated solutions.

2.4.2 Technical Barriers

Integrated solutions also face technical barriers including lack of knowledge and experienced professionals, final product quality and odour, feedstock management, and safety measures (Tab. 2.5). Although co-digestion of manure and crop residue has been practiced for a long time, AcoD of sewage sludge and organic waste flow is not yet widely practiced (Long et al., 2017). Lack of knowledge and operational experience is one main barrier for integrated solutions; Alvarez et al. (2014) argue that the lack of information on co-digestion from industry creates this situation (Mata-Alvarez et al., 2014). There are, however, numerous examples of applied co-digestion projects in recent scientific literature, summarized in Tab. 2.6. Examples can be found in the EU, United States, Japan and Australia. As the table reveals the majority of the AcoD projects are taking place in the most developed countries of the EU, including Denmark, Germany, Italy, Austria, France and Slovenia (Tab. 2.6). Furthermore, in most cases WWTP digesters are used for ACoD applications where the primary substrate is sewage sludge and co-substrates are industrial and agricultural waste. In Denmark, AcoD is practiced in digesters processing agricultural residues, not unexpected given agriculture's importance in the Danish economy. In France and in one plant in Italy, AcoD is used for organic waste co-digestion. In most cases, operation modes are Mesophilic, except in Denmark where Thermophilic digestion is used. Energy sufficiency has been reported in the case of five WWTPs.

All WWTP operators require training for the operations of the plant. In the case of integrated concepts, additional training is required to control the new processes, and account for varying interconnected flows and reactor conditions. Such expertise is not currently standard for the industry. Another key technical barrier is the quality of the final product. The quality of end-product depends largely on the quality of co-substrates. Depending on its source, bio-waste may contain up to 20% of inert impurities such as bones, glass, porcelain, plastic and tableware (Long et al., 2017), which besides affecting the quality of the end product, also affects the process operation. Bones, for example, are abrasive and can damage pumps and other equipment, while plastic affects final digestate quality and acceptability as a fertilizer. It is noted that all Italian co-digestion plants listed in Tab. 2.6 reported the presence of plastic in the digestate. Case et al. (2017) reports that in Denmark farmers argued that the fertiliser produced from secondary materials was of uncertain quality.

As an example of positive practice, in 2017 Germany modified its Fertilizer Ordinance and established limit values of inert impurities in substrates returned to soil (i.e., fertilizer, soil additives, growing media). The limit was set at 0.4% DM for particles larger 2 mm for waste paper, cardboard, glass, metals and plastic; and 0.1% DM for non-degraded films (modified DüMV, 2015). In Europe, two recent policy instruments, the Circular Economy Package (2018) and the EU Fertiliser Regulation (2019) attempt to solve the technical barrier relating to product quality. The former establishes that bio-waste be separated at sources and not mixed with other waste; while the latter establishes the guidelines for organic fertilizers manufactured from secondary materials and enters force in 2022. On the input side, feedstock supply properties due to seasonal or other variation, will affect the operation of the integrated facility, and should be planned upfront. Local roads leading to the treatment facility should be able to handle the loads and traffic. Sufficient physical space to handle co-substrate surpluses is also necessary. Due to additional potential hazards, co-substrate storage and handling must be performed in accordance with the highest safety standards and should not adversely impact existing WWTP operations.

Tab. 2.6: List of identified full-scale co-digestion projects worldwide.

Main Substrate	Plant Name	Location	Main substrate loading rate	Co-Substrate	Co-substrate loading rate	Biogas production	Electricity production	Energy sufficiency	Reference
Sewage sludge	Glenelg	Australia	N/A	Beverages waste Whey FOG	28 t/d	8,600 m^3/d	N/A	75%	Long et al., 2017; Krampe et al., 2010
	Joint Water Pollution Control Plant Casrson	CA, US	17 t/d	Bio-waste	2 t/d	N/A	N/A	97%	Shen et al., 2015
	Rovereto	Italy	90 t/d	Food waste	10 t/d	2,723 m^3/d	8 kWh/d	85%	Mattiolli et al., 2017; Naghiem et al., 2017; Cecchi and Cavinato,2019
	Treviso	Italy	100 t/d	Food waste	20 t/d	580 m^3/d	3 kWh/d	N/A	Long et al., 2017; Cavinato et al., 2013; Shen et al.,2015; Cecchi and Cavinato,2019; Bolzonella et al. 2006
	Viareggio	Italy	350 t/d	Bio-waste	3 t/d	860 m^3/d	6 kWh/d	N/A	Bolzonella et al. 2006; Shen et al., 2015
	Boden WWTP	Sweden	65 t/d	Food waste	4 t/d	1,600 m^3/d	7,700 kWh/d	N/A	Shen et al., 2015 ; Held et al., 2008
	Velenie	Slovenia	N/A	Bio-waste	4 t/d	N/A	N/A	N/A	Zupancic et al., 2008: Shen et al., 2015
	Prague	Czech Republic	N/A	Bio-waste	17 t/d	11,000 m^3/d	74,000 kWh/d	75%	Veolia
	Moosburg	Germany	120 t/d	Bio-waste dairy waste flows	40 t/d	4,500 m^3/d	5 kWh/d	83%	Long et al., 2017
	East Bay MUD	USA	2,650 t/d	Bio-waste FOG	120 t/d	35,000 m^3/d	N/A	N/A	Long et al., 2017; Shen et al., 2015; Nguyen et al., 2020
	Radeberg	Germany	112 t/d	Bio-waste industrial bio-waste	41 t/d	8 m^3/d	N/A	100%	http://www.bvr-radeberg.de/anlage/
	Baden-Baden	Germany	220 t/d	Bio-waste FOG	36 t/d	11,000 m^3/d	33 kWh/d	N/A	Blank uand Hoffmann, 2011; Shen et al., 2015
	Kurobe	Japan	80 t/d	Coffee Septic tank sludge	13 t/d	2,700 m^3/d	N/A	N/A	Long et al., 2017 https://www.swing-w.com/eng/solution/kurobe_p.html

Tab. 2.7: List of identified full-scale co-digestion projects worldwide (continuous).

Main Substrate	Plant Name	Location	Main substrate loading rate	Co-Substrate	Co-substrate loading rate	Biogas production	Electricity production	Energy sufficiency	Reference
Sewage sludge	Gloversville-Johnstown WWTP	NY, US	N/A	Dairy waste	N/A	11,000 m³/d	36 kWh/d	100%	Shen et al., 2015; Nguyen et al., 2020
	WWTP Zirl	Austria	6 t/d	Expired food FOG Coffee Grounds	43,253 t/d	4,000 m³/d	N/A	100%	Shen et al., 2015; Nguyen et al., 2020
	Millbrae WPCP	CA, US	106 t/d	FOG	11 t/d	N/A	N/A	68%	Shen et al., 2015
	South Baysie System Reedwood City WWTP	CA, US	945 t/d	FOG	13 t/d	N/A	N/A	N/A	Shen et al., 2015
	Annacis Island WWTP	Canada	43,138 t/d	FOG	1 t/d	N/A	N/A	0.5	Shen et al., 2015
	WWTP Gwinnett County	GA, US	772 t/d	FOG	88 t/d	N/A	N/A	0.5	Shen et al., 2015
	Grevesmuhlen	Germany	90 t/d	FOG	N/A	770 m³/d	5 kWh/d	1	Shen et al., 2015
	Douglas L. Smith Middle Basin WWTP	KS, US	18 t/d	FOG	33 t/d	N/A	N/A	50%	Shen et al., 2015
	Gresham WWTP	OR, US	227 t/d	FOG	34 t/d	12,500 m³/d	N/A	100%	Shen et al., 2015; Nguyen et al., 2020
	Braaunschweig WWTP	Germany	52,300 m³/d	FOG	14 t/d	5,086 m³/d	35,600 kWh/d	1	Veolia
	Gera	Germany	N/A	FOG	20 t/d	1,571 m³/d	11,000 kWh/d	100%	Veolia
	Görlitz	Germany	N/A	FOG, Soap	5 t/d	743 m³/d	5,200 kWh/d	0.75	Veolia
	Budapest South	Hungary	80,000 t/d	FOG dairy waste	286 t/d	5,000 m³/d	35,000 kWh/d	0.86	Veolia
	Budapest North	Hungary	N/A	FOG, Industrial organic waste	60 t/d	6,857 m³/d	48,000 kWh/d	90%	Veolia
	Pilsen	Czech Repu	76,000 t/d	FOG Yeast	8 t/d	2,714 m³/d	19,000 kWh/d	75%	Veolia
Manure	Lemvig Biogas Plant	Denmark	362 t/d	Bio-waste Sewage sludge	75 t/d	15 m³/d	N/A	N/A	Al Seadii et al., 2000
	Maabjerg Bioenergy	Denmark	1 t/d	Bio-waste Sewage sludge	770 t/d	124 m³/d	28 kWh/d	N/A	https://www.maabjergenergycenter.dk/
	Thorso	Denmark	230 t/d	Bio-waste Sewage sludge	32 t/d	8,000 m³/d	N/A	N/A	Al Seadii et al., 2000
	Blåbjerg	Denmark	222 t/d	Bio-waste dairy products Sewage sludge Fat form food processing	87 t/d	9 m³/d	N/A	N/A	Al Seadii et al., 2000
	Snertinge	Denmark	66 t/d	Sewage sludge	42 t/d	4 m³/d	N/A	N/A	Al Seadii et al., 2000
Bio-waste	Ferti-NRJ	France	83 t/d	Sewage sludge	21 t/d	12 m³/d	64 kWh/d	N/A	Al Seadi et al., 2001
	Camposampiero	Italy	82 t/d	Manure Sewage sludge	27 t/d	N/A	N/A	N/A	Long et al., 2017; Cecchi and Cavinato., 2015; Cecchi and Cavinato., 2019

2.4.3 Social Barriers

Until recently, water industry practitioners had generally failed to expand their expertise outside the traditional boundaries of conventional engineering. Guest et al. (2009) emphasizes that despite having technology available “absence of a holistic design methodology capable of including sociological factors” in “given geographical and cultural context” is hindering the implementation of resource recovery from wastewater. When it comes to integrated solutions, social barriers are important to consider. Social barriers are divided into public acceptance, informational barriers, inter-sectorial collaboration, and challenges with regarding primary waste collection (Tab. 2.5). Public acceptance of integrated solutions should not be underestimated, as nutrients derived from waste flows and applied as agricultural inputs are usually not desirable. Farmers may thus be hesitant to use these products. Barquet et al. (2020) argues that product design and innovative business models may help to eventually overcome this barrier, allowing fertiliser produced from secondary materials to be more competitive in application, quality and price with conventional fertilizers.

Another reason for social barriers derives from the fact that wastewater, waste and agriculture are traditionally separately managed. Furthermore, there is a disconnect between these sectors and their views on nutrients and energy. For the wastewater sector, nutrients are pollutants to be removed to achieve effluent discharge limits and preserve human health and the environment. The agriculture sector views nutrients as fertilizer to support plant growth. Sewage sludge, a product of a WWTP, has been traditionally classified and treated as organic waste regulated by the EU Waste Framework Directive.

To allow nutrient recovery and application as fertilizer for agricultural purposes, products declared as waste must fulfil requirements established by the EU Fertilizer Regulation for end-of-waste product. Until recently this was an obstacle, as the Fertilizer Regulation was certifying primary mineral compounds (de Boer et al., 2018). The new EU Fertilizer Product Regulation (2020) regulates organic fertilizers manufactured from secondary materials. This should accelerate the implementation of integrated projects.

Differences in management approaches, as well as views on nutrients in these three sectors, has hindered collaboration across sectors, which in turn hinders integrated concepts (Barquet, 2020). Integrated solutions require a collaboration of diverse stakeholders who must meet demanding requirements set by the diverse regulations (e.g., UWWTD, Nitrate Directive, Fertilizer Regulation, Waste Framework Directive). This is a challenging task requiring expertise and continual stakeholder dialogue. In actuality, the idea of introducing odoriferous organic waste flows and agricultural residues to WWTPs to recovery nutrients tends to raise concerns of the local population. This then influences political decisions, as decision makers try to avoid negative publicity. Thus, the fate of integrated options depends on the leadership and communication skills of decision makers whose job it is to educate the public of the real risks and the environmental and economic benefits. Here, information barriers play a crucial role. Decision makers need to understand and articulate the benefits and to be transparent regarding the planning process, evaluation of waste flows, and costs and financing.

Challenges with primary waste selection on the local level are an additional potential social barrier. Although practiced in Germany, Italy and Japan, primary waste separation is still an emerging concept worldwide and its implementation requires good governance and end users committed to the effort.

2.4.4 Legal Barriers

Regulatory uncertainties and differences across governmental agencies are the main legal barriers (Tab. 2.7) for implementing integrated projects. The primary mandate and focus of WWTP is to meet the regulatory discharge limits. Hence, implementation of AcoD and nutrient recovery may be challenging for WWTP operators, as they would need to further understand regulations for waste materials and renewable energies. Bozonella at al. (2018) and Vaneeckaute et al. (2017) argue that the application of AcoD remains hindered mainly by non-existing and/or unclear regulatory frameworks. The mixing of wastes for AcoD implies that the digestate is subject to strict and conservative regulations falling under the responsibilities of different sectors. For example, strict limits of nitrogen and phosphorus in the digestate (Vaneeckaute et al., 2017), plus the fact that most of the digestate products are not classified (Bozonella et al., 2018) remains a key constraint. Furthermore, co-digestion substrates are normally classified as waste and thus subject to waste regulation control (Vaneeckaute et al (2017). In view of all this, obtaining all the necessary permits for an integrated project is a challenge.

The growing dependency on phosphorus and its geopolitical importance was officially recognized by the EC in 2014 by listing phosphate rock as a critical element; this has facilitated discussion concerning its recovery potentials (Barquet et al., 2020). Harmonizing policies across different sectors is necessary and should not inhibit waste reuse opportunities. In practice, there are challenges to overcome concerning the responsibilities between management authorities and institutions (Daigger et al., 2017).

2.5 Serbian Perspective

Committing to a paradigm change toward integrated resources management is not a simple task, as such concepts incorporate different sectors and diverse stakeholders, and aim to provide alternate benefits such as water re-use and energy and nutrient recycling (Hering et al., 2013). A considerable obstacle lies in the existing robust infrastructure in developed countries which have not been designed for multipurpose use. Hence, transition countries with lower levels of infrastructure may provide more suitable grounds for this new approach. To achieve this, diverse scientific and engineering disciplines must collaborate, backed by the appropriate political support, legislation, and effective management. The selected case study for this research is in Serbia; this Chapter presents in-depth discussions of the Serbian sectors of water, waste, energy and agriculture and their suitability for applying in integrated solutions.

2.5.1 General Information

Serbia is a Danube-bordering, land-locked country on the crossroad of central and southeast Europe on the Balkan Peninsula (Fig. 2.19). It has a population of ca. 7

Mil. people and occupies a territory of 88,360 km^2. Serbia is a middle-income country with GDP $51.4 billion ($7,378 per capita) in 2019 (World Bank, 2020). Its economic strength is comparable to the new EU countries, Croatia, Bulgaria and Romania. The per capita GDP purchase power was 41% of the EU average in 2019 (EC, 2020b). Because of global economic conditions, Serbia has twice recently experienced a recession – in 2009 and in 2012. In 2014 the country was affected by severe flooding which adversely affected the agriculture and energy sectors. Since 2015, Serbia's economic growth has been positive, reaching 4.3% in 2018, while government debt fell to 54% of GDP in 2018 (EC,2020b).

Fig. 2.19: Location of Serbia.
Source: (World Bank, 2015)

Serbia was granted EU candidate status in 2012, and since 2014 it has begun negotiations with the EC for accession into the EU. This status obliges the Serbian Government to align its laws with EU standards.

2.5.2 Wastewater Sector

According to the most recent available data (Tab. 2.8), in 2018 around 72% if generated wastewater was evacuated by a 16,800 km long sewer network (SORS, 2019). However, only 17% of the evacuated wastewater is treated, with 70% of that portion receiving secondary treatment and 20% tertiary treatment (SORS, 2019). There are around 50 WWTPs in Serbia serving 600,000 inhabitants ("Official Gazette of RS" No. 3/2017). Eighteen facilities are out of operation, while the rest are mainly overdesigned and not operating in accordance with design parameters ("Official Gazette of RS" No. 3/2017). Due to inadequate financing of the sector in the last decades, water infrastructure is timeworn, and as such is prone to damage by natural phenomena and other risks (GRS, 2015a). The Danube River is the ultimate recipient of all generated wastewater in Serbia, 43% via direct discharge and the balance via its tributaries (SORS, 2019).

Tab. 2.8: Wastewater management data Serbia for 2018.
Source: (Adopted from SORS, 2019)

Total generated municipal wastewater	404 Mil.m^3/a
Evacuated municipal wastewater	293 Mil.m^3/a
Domestic wastewater	73 %
Industrial wastewater	27 %
Treated municipal wastewater	49 Mil.m^3/a
Secondary wastewater treatment	34 Mil.m^3/a
Tertiary wastewater treatment	10 Mil.m^3/a

Rural households account for 40% of all households in Serbia and generate 111 Mm^3 wastewater annually, which is collected in septic tanks (SORS, 2019); household septic tanks in village households are highly common. These systems are often unsealed, poorly maintained, and discharged into surface waters or drained into groundwater. Often, after years of poor maintenance septic tanks become clogged and are replaced by a newer septic system. Bad septic practices have contaminated groundwater sources in parts of Serbia, despite the fact that 73% of Serbia’s drinking water is supplied by groundwater (World Bank, 2015). Additional pressure on the receiving waters comes from the agricultural sector and its 630,000 agricultural holdings (FAO, 2020).

Besides poor infrastructure and outdated, inefficient wastewater treatment, the sector is challenged by inadequate public awareness of sustainable water management. The average drinking water consumption is high, averaging 300 l/(cap*day), versus the EU average of 122 l/(cap*day) (EP, 2020). Water system losses are estimated at 40% (Dimkic et al, 2020). Meanwhile, local water utility costs are very low, averaging 0.7 EUR/m^3 (Dimkic et al, 2020), making them highly affordable even for Serbian households, where those expenses account for only 1,2% - 1,9% of available household income (World Bank, 2015).

Additional issues in Serbia include a lack of reliable data for WWTP design (Flanders, 2017), and challenges with institutional capacity governing the water sector are manifold. As shown in Fig. 2.20, on the national level there are six ministries responsible in part for the water sector. Before a service provider (in Serbia, a Public Utility Company, or PUC) may act, it must consult numerous Ministries and national and regional Institutions (Fig. 2.20). Lack of clearly defined institutional roles and responsibilities, compounded by inadequate and ineffective coordination, places many obstacles and delays in sector restructuring (Flanders, 2017, World Bank, 2015).

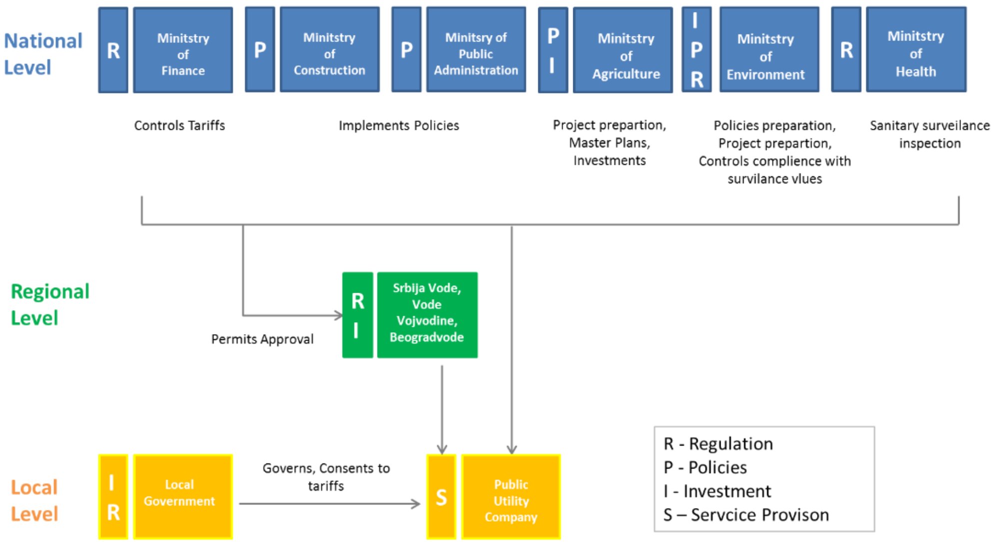


Fig. 2.20: Institutional Capacity governing the water sector in Serbia. Source: (Adopted from World Bank, 2015)

The low number of treatment facilities in Serbia results in significant organic and inorganic discharge. According to monitoring activities of the Serbian Environmental Protection Agency (SEPA), 41% of Serbian water bodies are rated as “poor” in terms of chemical water quality (SEPA, 2015). Furthermore, IPCDR (2015) reported that Serbia generates the highest organic, phosphorus and nitrogen loads in the entire Danube basin, of which 80% is due to inadequate wastewater treatment (IPCDR, 2015). Organic load accounts for 42% (106,200 tCOD/a), phosphorus for 28% (4,400 tP/a) and nitrogen for 19% (16,400 t N/a) of the overall Danube basin discharge loads (IPCDR, 2015). Therefore, nutrient removal from wastewater is an environmental priority.

The adoption of the EU water acquis in Serbia’s national legislation has been moderate (EC, 2020b). Although the Water Management Strategy (Official Gazette of RS" No. 3/2017) is in line with the Water Framework Directive, the biggest challenge remains the lack of an Action Plan for implementation (EC, 2020b). The UWWTD is only partially transposed into Serbia legislation by the Law on Water and by two Regulation which set pollutant discharge limits - the Regulation on the Establishment of Emission Limit Values and Deadlines for Their Achievement (RELV) ("Official Gazette of RS" No. 1/2016) and the Regulation on Limit Values for Pollutants in Surface Waters, Groundwater and Sediments, and Deadlines for their Achievement ("RS Official Gazette" No. 50/12). According to the RELV, which sets abatement limits from point sources to the recipient, nitrogen and phosphorus removal is required in agglomerations larger than 10,000 PE and 1,000 PE, retrospectively (Tab. 2.9). Thus, the phosphorus removal limit is stricter than the EU Water Framework Directive, which requires removal from 2,000 PE.

The Regulation also establishes emission limits for specific categories of chemical pollutants commonly discharged in 50 industry sectors. Discharge of raw industrial wastewater into the sewer system and combining with domestic wastewater prior the treatment is prohibited ("Official Gazette of RS" No. 1/2016). All industrial wastewater must be strictly separated from domestic wastewater, and must be either treated on site and then discharged into a permitted receiving body, or pre-treated to municipal wastewater standards and discharged into the sewer.

Tab. 2.9: Effluent standards for treated municipal wastewater in Serbia according to RELV. Source: (Official Gazette of RS, 2016)

Parameter		Limit value	Removal rate
COD		125 mg/l	75%
BOD		25 mg/l	70-90 %
	If no negative affect to recipient	40 mg/l	
TSS	≥ 10,000 PE	35 mg/l	90%
	2,000 – 10,000 PE	60 mg/l	
N	≥ 100,000 PE	10 mg/l	70-80%
	10,000 – 100,000 PE	15 mg/l	
	≥ 1,000 PE	1 mg/l	80%

Additionally, required if receiving body is used for water supply, irrigation and/or recreation

Coliform Bacteria	10,000 / 100 ml
Faecal Coliforms	2,000 / 100 ml
Faecal Streptococci	400 / 100 ml

EC (2020b) reported that alignment of national legislation with the EU acquis requires strengthening administrative capacity, in particular monitoring, enforcement and inter-institutional coordination. Main obstacles remain a lack of human and financial resources and lack of data (EC, 2020b). The adoption and implementation of the EU Acquis will require an investment of €5 billion, including for the construction of 320 WWTPs (Flanders, 2017).

2.5.3 Waste Sector

Serbia has undergone rapid urbanization in the last 40 years, transforming lifestyles and increasing consumption and waste generation (Bajic at al., 2015). As Fig. 2.10 indicates, Serbia's waste generation rate of 268 kg/(cap*a) (2016) is significantly lower than the EU-27 average of 488 kg/(cap*a) (2016), and roughly in line with SEE countries of comparable development levels, such as Romania (261 kg/(cap*a); 2016) (Eurostat, 2020). Serbia's total annual solid waste generation is ca. 2.4 Mil.t (Vujic et al., 2020, SEPA, 2014, Bajic at al., 2015, Vujic at al., 2015). Waste collection is organized for ca. 60% of the population, out of which 90% is disposed of at seven sanitary landfills serving ca. 20% of the total population; 157 official registered landfill sites; and roughly 3,500 dumping sites (SEPA, 2019; Vujic at al., 2015). Waste is collected as mixed, with some examples of primary selection of plastic and paper. The overall recycling rate of MSW in Serbia is only 3% (EC, 2020b). Vujic et al. (2020) reported that annually ca. 20,000 tons of waste is burned in cement factories. Over 90% of the landfills do not monitor any impact on soil, air or water. The collection is predominantly organized by public utility companies (PUC); with only 5% of the waste collected by private collection system (Vujic et al., 2015).

The morphological composition of MSW in Serbia is shown in Fig. 2.21. As seen, the main share (50%) is bio-waste, of which 30% is gardening waste and 70% other biodegradable waste. Average mixed waste moisture is 32.5 - 37.5% (Vujic et al., 2015). As MSW is not source separated in Serbia, up to 96% of the collected bio-waste is disposed of in landfills, many of which are not constructed according to EU regulations, while the balance is composted (Vujovic et al., 2020, Stanisavljevic et al., 2015).

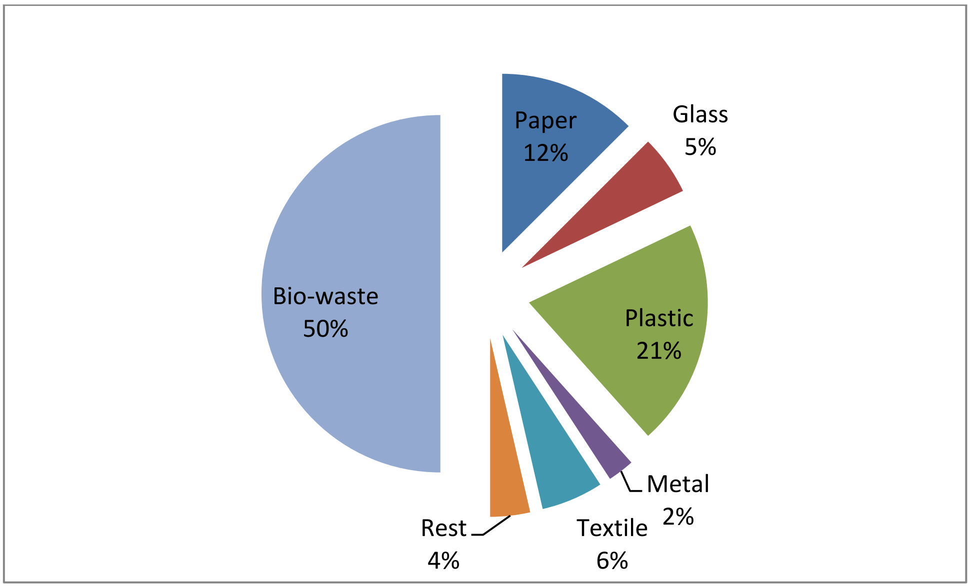


Fig. 2.21: Morphological composition of waste in the Republic of Serbia. Source: Modified from (Vujic at al., 2015)

]

A waste utility fee is assessed by local governments; these vary throughout the country. Fees are most commonly assessed based on square meters of living space, and generally range from 0.026 - 0.035 EUR/(m^2*month), resulting in an average annual household fee of 30 - 35 EUR (Vujic et al., 2015). The collection is ca. 70% for households and 100% for industry (Vujic et al., 2015). This fee is generally only sufficient to cover collection and transport, while waste management is not included. Due to the inherent inefficiency of this model, the central government must subsidize waste management at the local level. According to Vujic et al. (2015), increasing the waste utility fee by 100% is necessary to cover the costs of sanitary landfilling. Several strategic investments in the sector have been supported by EU Pre-Accession Funds and other financial institutions.

The EC (2020b) has recognized Serbia’s effort to harmonise its waste management legislation with that of the EU. The main governing pieces of legislation are Law of Waste Management ("RS Official Gazette" No. 36/2009, 88/2010 i 14/2016), Decree on Waste Landfilling ("RS Official Gazette" No. 92/2010) and Law on Packaging and Packaging Waste ("RS Official Gazette" No. 36/2009). The main strategic document is the National Waste Management Strategy; the strategy for 2019-2024 remains in the process of adoption. According to the strategy, the overall waste management system is envisioned as 27 regions, with as many sanitary landfills. Groups of municipalities that comprise in total at least 200,000 inhabitants can form a region, for which one sanitary landfill is foreseen. However, like in the wastewater sector, an Action Plan to implement the strategy is missing (EC, 2020b). One specific obstacle with respect to EU harmonization is that reduction targets for landfilled organic waste are postponed in Serbia, with EU goals having been set by the EU Landfill Directive. The EC (2020b) emphasized that Serbia needs to “redouble efforts to close its non-compliant landfills and invest in waste reduction, separation and recycling”. And here again, the lack of available, reliable data on which to base designs and decisions remains a persistent problem (Vujovic et al, 2020; Bajic at al., 2015, Vujic at al., 2017).

2.5.4 Agriculture Sector

Serbia has favourable conditions for agriculture, including good soil quality and moderate continental climate, providing conditions for prosperous agricultural production and a long-lasting tradition of family farming (FAO, 2020). The largest agriculture activates are concentrated along the Danube and Sava Rivers in the northern province of Vojvodina, and along the Morava River in central Serbia. After industry and energy, agriculture represents the third largest GDP contributor of Serbia's economy, at ca. 6% (SORS, 2019). This is significantly higher than the EU average, where agriculture contributes 1% to the GDP (EUROSTAT, 2020). In Serbia 15% of the workforce (ca. 680,000 people) are employed in the agricultural sector (SORS, 2019); agriculture accounts for 21% of Serbian exports (FAO, 2020).

Serbia has 5 Mil. ha of agricultural land (0.7 ha per capita), of which 71% is cultivated (0.5 ha/capita) (Eko bilten, 2017). The average utilized agricultural area in Serbia is 5.4 ha/farm household (FAO, 2020), far below the European average of ca. 16 ha/farm household (EUROSTAT, 2020). In Vojvodina in the north, there are much larger farms, averaging 10.9 ha/farm household. Roughly half of all farms are small family farms smaller than 2.0 ha mainly in southern and eastern Serbia (Bogdanov and Rodić, 2014; Bogdanov et al., 2017, FAO, 2020). Irrigation is applied to only 1.25% of the cultivated surface, primarily sprinkling systems, the entire demand for which comes from the Danube River catchment area (SORS, 2018). This represents a significant threat for the future, as climate change projections estimate an increase of average annual temperature by 1.5 - 2.2ºC and a decrease of annual precipitation of 1.1 - 3.5% (USAID,2017). Therefore, Serbia's agriculture sector is likely to become increasingly dependent on irrigation. In the last ten years, there have been three severe droughts in 2012, 2015 and 2017, all of which severely affected crops and reduced yields by more than 20% (FAO, 2020).

Approximately 90% of Serbia's arable land is privately owned by 630,000 registered family farms, while the rest is divided among 3,000 agricultural enterprises (ca. 12% cooperatives) (Bajramovic et al., 2016; FAO, 2020). In gross terms, crop production dominates livestock production, contributing 67% of the total agricultural activities (Bajramovic et al., 2016; FAO, 2020). The most cultivated crops are maize (7 Mil.t in

2018; 48% of crop mix), wheat (3 Mil.t in 2018; 20% of crop mix) and sugar beet (2,4 Mil.t in 2018; 18% of crop mix) (SORS,2020). In 2018, Serbia had 21,7 Mil. livestock units, where poultry contributes with 75% of the total number of animals, followed by pig (13%) and sheep farming (8%) (SORS,2020). The average number of livestock per holding is 4.1 (Bajramovic et al., 2016).

Annual available biomass potential from Serbia's agricultural sector is estimated at 1.67 Mil.t/a (GRS, 2016, UNEP, 2018), of which 72% is crop residues, 16% oil crop by-products, 7% manure, 4% fruits residues and 1% processing industry waste (UNDP, 2018). Given such a supply, waste biomass from agriculture (both crop and livestock) can play a role in energy and nutrient recovery. This potential remains almost completely untapped, with a utilization rate estimated at just 2% (GRS, 2016). Traditionally waste biomass from field crops is burned in place (UNDP, 2018), resulting in smoky emissions, energy and nutrients losses, humus damage and disruption of microorganisms, degrading soil quality (Dodic at al., 2010). Livestock residues are similarly considered valueless, remaining underutilized as crop application, and often illegally discharged into the nearest river or stream.

In 2020, the EC evaluated that conformance of the Serbian legislation with the EC Acquis in the agricultural sector is progressing, but it remains slow (EC,2020b). The two guiding documents for approximating the EU Common Agriculture Policy (CAP) are Law on Agriculture and Rural Development (Official Gazette no 10/2013), which defines all subsidies and eligibility; and Agricultural Rural Development Strategy 2014-2024 (Official Gazette, no 85/2014), which defies the part of the approximation with the CAP for the 10-year period.

2.5.5 Energy Sector

Serbia's energy intensity is almost five times higher than the EU average (OECD, 2018). Domestic energy production in 2017 relies mainly on coal (70% of primary energy), crude oil (9%), wood (10%). hydropower (8%) and natural gas (4%) (SORS; 2020). According to the World Bank, energy consumption in Serbia is 1,900 kg of oil equivalent per capita, approximately equal to the global average and significantly lower than the EU average (3,300 oil equivalent per capita) (World Bank, 2014).

Serbia is one of the few nations in the world that does not depend on nuclear energy at all. Serbia is energy-dependent, reaching 33.5% dependency in 2010 (GRS, 2016). This dependence is average compared to the EU 27 countries (GRS, 2016, Djurisic-Mladenovic et al., 2018). Due to 6-7% annual increases in energy consumption (Dodic at al., 2010) energy dependency will likely continue to grow (Djurisic-Mladenovic et al., 2018), as oil and gas reserves comprise less than 1% of total energy reserves (Tesic at al., 2011, Djurisic-Mladenovic et al., 2018). The balance is predominantly lignite coal, of which 76% of reserves are located in Kosovo (Tesic at al., 2011). The most imported energy carriers are oil and natural gas, which cover 70% and 85% of demand retrospectively (GRS, 2016).

The flooding in 2014 severely damaged Serbia’s energy sector, costing an estimated EUR 184 Mil. (Karovic Maricic et al., 2018). Being a landlocked country, Serbia is isolated from main energy markets and terminals. Energy import is thus primarily via pipeline, which raises questions regarding energy stability and places Serbia in its dependent, disadvantageous position. Serbia is currently threatened by an acute gas crisis, as its only gas supply originates from Russia, via Ukraine. Since the South Stream pipeline project was abandoned, the remaining present alternative is for Serbia to join the South Corridor and thus receive gas from the Caspian Sea and via Azerbaijan.

The Energy Law ("RS Official Gazette" No. 145/2014) is the governing legislation document in the energy sector. Energy policy has been harmonized with the EU Acquis, including by transposing the EU Third Energy Package, which further liberalizes the energy market within the EU (OECD, 2018, Karovic Maricic et al., 2018). The Energy Development Strategy 2025-2030 is the main implementation document, which establishes priorities, including to increase energy security, develop domestic and regional energy markets, and provide sustainable energy development (GRS, 2016).

Serbia has set a target to achieve 27% of total consumption to be provided by renewable sources by 2020, compared to 20.1% actual in 2009 (GRS, 2013; Banjac et al., 2013). Currently, there are no official data on available communal sewage sludge quantities which could be used as an organic material flow for energy generation. The National Environmental Approximation Strategy forecast sewer connection rate increasing to 83% of the population by 2025 (GRS, 2011); if this proves correct, then ca. 7.3 Mil.t/a sewage sludge will be generated, requiring new management practices. OECD (2018) reported that lacking financial resources and skilled staff in the sector limits regulators effectiveness to carry out their responsibilities. Incentives for renewable energy generation have been in place since 2013.

3 Materials and Methods

3.1 Methodological Approach

Fig. 3.1 overviews the research methodology to meet the aim and answer research postulates. The research procedure consists of three major parts: 1) Data Collection; 2) Decision Support Tool Development; and 3) Decision Support Tool Testing (Fig. 3.1). First, the Case Study Region (CRS) was selected, and relevant flow and discharge data was collected (Step 1 below; see Fig.1.2). Next, a Decision Support Tool was developed (Step 2 below) as a Microsoft Excel template. Based on the user preferences and input data, the tool calculates, schematically presents and compares two Variants of sixteen integrated. Lastly, the tool was tested (Step 3) based on the collected and evaluated CSR's data.

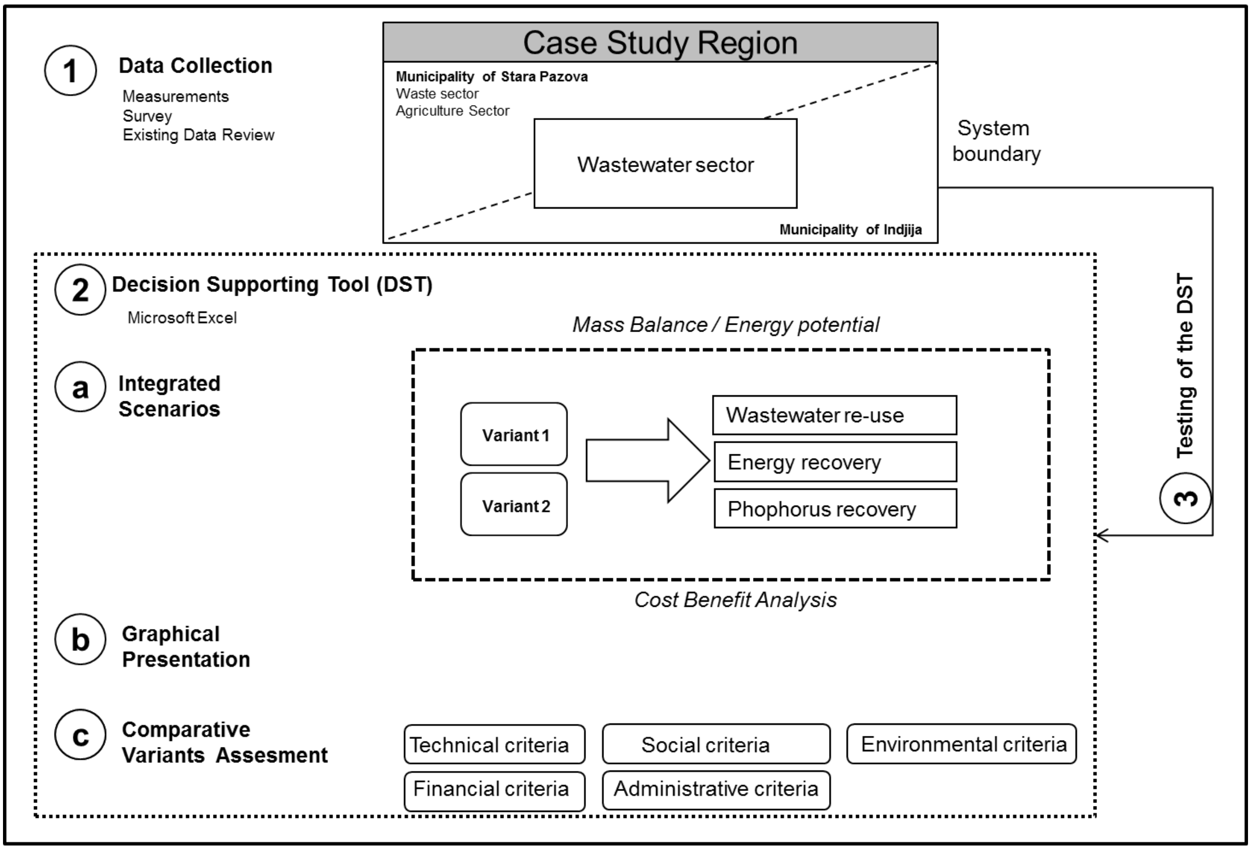


Fig. 3.1: Research procedure and methods.

3.2 Case Study

The CSR consists of two neighbouring Serbian municipalities, Stara Pazova and Indjija, adjacent to the Danube River and located in the north of Serbia in the autonomous province of Vojvodina (Fig. 3.2). The two municipalities have a combined population of roughly 114,000 inhabitants and occupy an area of 736 km^2. The municipalities share a common regional wastewater sewer system (regional collector), 75 km length (Fig. 3.3) which outflows on the territory of the municipality of Stara Pazova. Due to this specific situation, the sewer evacuates wastewater from both municipalities, so that the “system boundary” is set to be the geographical boundaries of the two municipalities. For bio-waste flow, the system boundary is set to be the boundary only of the municipality Stara Pazova (Fig. 3.1).

Fig. 3.2: Location of the CSR.

The CSR has 20 settlements, out of which four are urban: Indjija, Stara Pazova, Nova Pazova and Novi Banovci (Tab. 3.1); the remainder is considered rural and occupy 85% of the territory. Crop and livestock production and agro-processing (crops, meat, dairy and other food) are the main economic activities of the rural citizens. The urban population is oriented towards manufacturing and industry, in sectors including wood, metal and machinery, plastics, textiles and chemicals. There are ten industrial zones in the region: eight in Stara Pazova totalling 1,500 ha; and two in Indjija of 735 ha. The CSR has well-developed traffic and transport infrastructure and networks, including river ports and proximity to Belgrade's Nikola Tesla International Airport.

Tab. 3.1: CSR settlements and population.
Source: (Official Gazette of RS, 2014)

Manicipality of Indjija		Manicipality of Stara Pazova	
Settelment	Population	Settelment	Population
Beska	5,783	Belegis	2,973
Indjija	26,025	Vojka	4,752
Jarkovci	593	Golubinci	4,721
Krcedin	2,429	Krnjasevci	845
Ljukovo	1,525	Nova Pazova	17,105
Maradik	2,095	Novi Banovci	9,443
Novi Karlovci	2,856	Stara Pazova	18,602
Novi Slankamen	2,994	Stari Banovci	5,954
Slankamenacki vinograd	253	Surduk	1,397
Stari Slankamen	543		
Cortanovic	2,337		
Total	47,433		65,792

Domestic wastewater is evacuated from 35% of the population, or roughly. 42,000 inhabitants; the connection rate is 55% in Injdija (26,000 inhabitants) and 22% in Stara Pazova (16,000 inhabitants). Industrial wastewater is only partly evacuated (ca. 50%) and pre-treated to municipal wastewater quality; it accounts for ca. 23% of the total municipal wastewater volume. The collector is built as a separate sewer system consisting of a main gravity sewer with pumping stations with an outfall ending on the territory of Stara Pazova in the settlement of Novi Banovci, where it is connected to the military collector coming from the Military Airport "Batajnica". Ultimately, the wastewater is discharged into the Danube River without any treatment. The balance of the generated domestic wastewater is collected in septic tanks and ultimately discharged at one of numerous locations on the Danube. Industrial wastewater not evacuated by the collector is either collected in septic tanks or evacuated by the several channels to the Danube. Presently both municipalities are extending their sewer network coverage to 100%, with a planned future WWTP to be located in Stara Pazova.

The CSR has a continental climate, with four seasons and relatively high-temperature variability: summers are warm and dry, winters are cold with frequent snow, and spring and autumn have moderate temperatures with higher precipitation. The average annual precipitation is approximately 650 mm, distributed uniformly over the year.

3.3 Data Collection

The data collection for this research lasted two years, from January 2013 through December 2014. Primary and secondary data sources were used. As a first step, available data was collected from official reports, including state statistical records, municipal records and national treasury of Serbia. Due to poor and inconsistent data, a measurement campaign and surveys were used. To estimate generated sewage sludge quantities, a wastewater measurement campaign was conducted. In addition, a survey evaluating the industrial impact on wastewater quality was performed (Appendix 1). Two additional surveys were used to estimate bio-waste and agricultural residues (Appendixes 2 and 3).

3.3.1 Measurement Campaign

Serbia’s national legislation obligates municipalities to test wastewater compositions twice per year using grab samples, while flow rate measurement is not required. Therefore, to characterize municipal wastewater in the CSR a wastewater measurement campaign was planned and performed in the scope of this research. The campaign measured wastewater flow and pollutant concentrations in Stara Pazova, from June 17 through December 6, 2014 (179 days). The main objectives of the measurement campaign were to ascertain wastewater pollutant load ranges and to calculate sewage sludge generation post-treatment. In addition, to help fill data gaps related to design norms for WWTPs in Serbia, inhabitant-specific pollutant loads for local Serbian conditions were calculated, and then compared with analogous values of German and American design guidelines. Lastly, specific recommendations are provided.

3.3.1.1 Determination of Sampling Location

To ensure a representative measurement campaign location, three possible locations were pre-selected, were visited and evaluated. As the regional collector outflows in the municipality of Stara Pazova, possible sampling locations were identified and inspected moving upstream. The first inspected sampling location was at the discharge of the regional collector (settlement Novi Banovci), which covers 100% of the existing sewer catchment area (42,000 inhabitants). Due to the location’s inaccessibility, it was deemed unsuitable. The second inspected location was a manhole of the trunk sewer, located within the bounds of the military complex Batajnica. This location covers ca. 95% of the sewer catchment area, although it is not easily accessible, being located within the military complex and requiring permits for entry. The third and final inspected location, which covers 90% of the sewer catchment area, is in the settlement Nova Pazova at the pumping station no. 1 (PS1); this location was deemed acceptable. As Fig. 3.3 shows, the selected sampling location on PS-1 is relatively isolated, though accessible from the main regional road, has electricity available, and it is locked and supervised by the Waterworks. PS-1 comprises two pumps installed in the mid 1990’s. Municipal wastewater produced in Indjija and Stara Pazova evacuated by the regional collector reaches PS-1 where it is collected in a sedimentation basin prior to discharge into the Danube River.

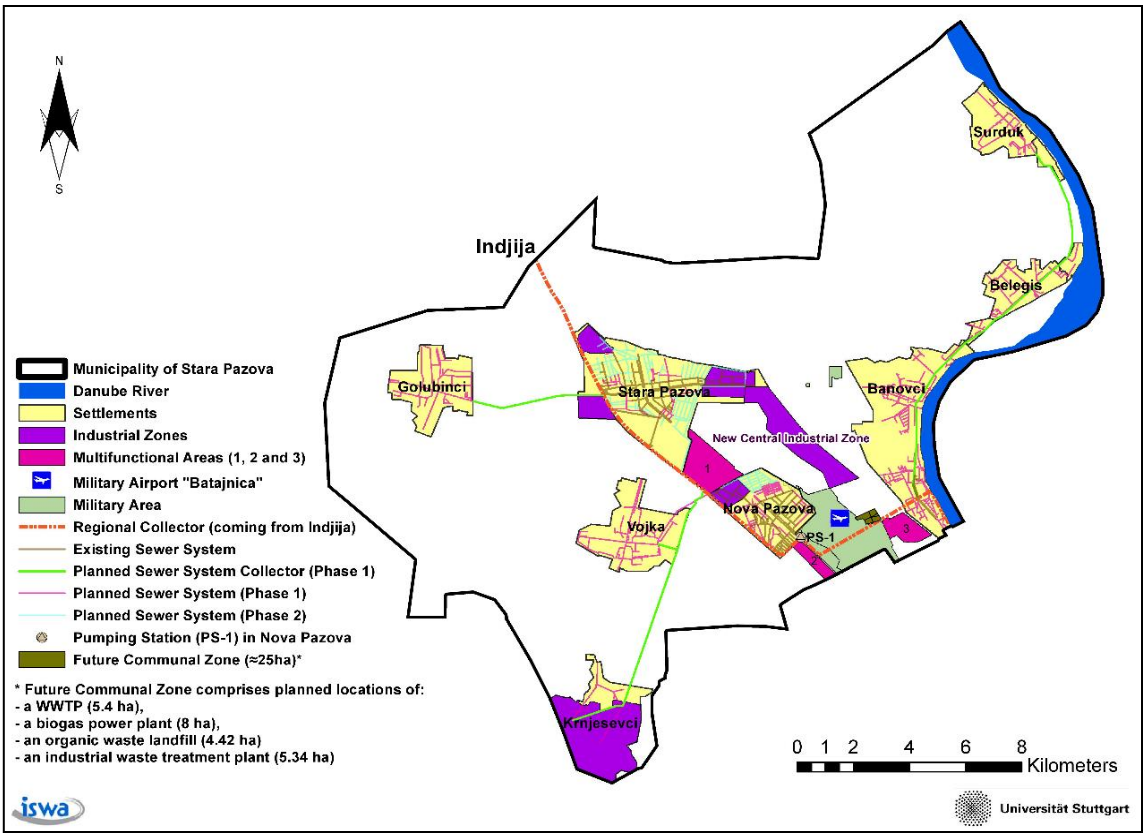


Fig. 3.3: Sewer network system in the municipality of Stara Pazova.

3.3.1.2 Measurement Campaign

As the CSR has a continental climate and the fact that the sewer system is a “separated” type, the measurement campaign was planned in three phases covering both wet and dry weather periods. During the campaign, a total of 114 samples were collected, of which 101 were 24-hour composite samples and 13 were two-hour composites (Tab. 3.2). The campaign covered all days of the week during all three seasonal phases (Tab. 3.3).

Tab. 3.2: Phases of the measurement campaign.

	Total precipitation	No. 24h composite sample	No. 2h composite sample
Phase 1: 17.06. - 20.07.2014	94.27 mm	34	
Phase 2: 21.07. - 02.11.2014	110.3 mm	34	1
Phase 3: 03.11. - 06.12.2014	49.9 mm	33	12
Total	254,47	101	13

Tab. 3.3: Detailed schedule of measurement campaign (17.06 – 07.12.2014, Stara Pazova).

Date			Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	No. Samples
1. Phase	Week 1	17.06-22.06		X	X	X	X	X	X	6
	Week 2	23.06-29.06	X	X	X	X	X	X	X	7
	Week 3	30.06-06.07	X	X	X	X	X	X	X	7
	Week 4	07.07-13.07	X	X	X	X	X	X	X	7
	Week 5	14.07-20.07	X	X	X	X	X	X	X	7
2. Phase	Week 6	21.07-27.07	X(2h)							1
	Week 7	28.07-03.08		X	X	X				3
	Week 8	04.08-10.08					X	X		2
	Week 9	11.08-17.08		X	X					2
	Week 10	18.08-24.08						X	X	2
	Week 11	25.08-31.08				X	X	X	X	4
	Week 12	01.09-07.09	X	X						2
	Week 13	08.09-14.09			X	X				3
	Week 14	14.09-21.09					X	X	X	3
	Week 15	22.09-28.09	X							1
	Week 16	29.09-05.10		X	X	X				3
	Week 17	06.10-12.10					X	X	X	3
	Week 18	13.10-19.10	X							1
	Week 19	20.10-26.10		X	X					2
	Week 20	27.10-02.11				X	X	X	X	4
3. Phase	Week 21	03.11-09.11	X	X	X	X	X	X	X	7
	Week 22	10.11-16.11	X	X	X	X	X	X	X	7
	Week 23	17.11-23.11	X	X	X	X(2h*12)	X	X	X	18
	Week 24	24.11-30.11	X	X	X	X	X	X	X	7
	Week 25	01.12-07.12	X	X	X	X	X	X		5
									TOTAL	**114**

Phase 1 (wet weather) was set at the outset of summer, conducted from June 17 through July 20, 2014, when the heaviest rainfall typically occurs. During Phase 1, samples were collected daily, resulting in a total of 34 24-hour composite samples. Phase 2 (dry weather) was conducted from July 21 through November 2, 2014. During this phase, it was planned to sample in an alternating sequence manner; however, due a failure on the auto-sampler during weeks 6, 8 and 10, the schedule was adapted. During the second phase, 34 24-hour composite samples and one 2-hour sample were collected. Phase 3 (dry weather) took place from November 3 through December 7, 2014, a relatively dry period. During Phase 3, a total of 33 24-hour and twelve 2-hour composite samples were collected. The Phase 3 period may be characterised as the most representative of the measurement campaign because during the five-week period, there were six rain days. On one occasion, November 18, rain was forecast, so the sampler was set to take twelve 2-hour samples to ascertain variations and effects. Temperature and hourly precipitation measurements were recorded with a mini weather station owned by the company “Delta Agrar” in Stara Pazova and delivered on the author’s request once per week.

3.3.1.3 Analytics

Wastewater flow was measured continuously during the entire period of the campaign with an ultrasonic flow-meter type “Prosonic S FDU91/ FMU 90” produced by *Endress+Hauser*. The public company Waterworks Stara Pazova installed the flowmeter in location at PS-1, in accordance with turbulent flow and homogeneity of the collected wastewater sample, downstream of the pumps (i.e., if pumps are not working, flow is recorded as zero). The flow measurement equipment features a probe installed in the DN900 collector channel and data logging equipment. Wastewater flow values were recorded in 15-minute intervals.

Wastewater samples were gathered using a portable auto-sampler *MAXX Mess- und Probenahmetechnik GmbH* (Type: TP 5C-24). The sampler was installed in cooperation with Waterworks and the *Institute for Occupational Health*, Novi Sad at the selected measurement location at PS-1 and set to operate in “time proportional” regime. The sampler was set to withdraw 40 ml of wastewater every 10 minutes and collected in six PVC bottles of 1-liter volume. The six bottles were then gathered into a canister of 6-l volume providing a total daily sample volume of 5,760 ml. The canister was appropriated labelled and immediately transported to the Laboratory of the *Institute for Occupational Health*, Novi Sad for analysis (60 km distance). Sampling, transport and conservation of the samples was done in accordance with Serbian Standard SRSPS ISO 5667 (‘’Water quality –Sampling’’ – Part1, Part 3 and Part 10). A complete list of analysed parameters and the method used is presented in Tab. 3.4. Wastewater sampling and laboratory analysis were done by the *Institute for Occupational Health*, Novi Sad, with results delivered to the author as raw data. Before evaluation of the delivered data, the data set was checked for outliers. The measured data was then input and evaluated using Microsoft Excel.

Tab. 3.4: List of analysed parameters and analytic methods used in the measurement campaign.

Parameter	Conservation	Place and deadline of analytics	Equipment used	Analytic Method
Air temperature	No	On-site	Digital Thermometer	EPA 170.1:1974
Wastewater temperature	No	On-site	Digital Thermometer	EPA 170.1:1974
Colour	No	On-site		
Odour	No	On-site		
Turbidity	No	On-site		
pH	Refrigerator	Laboratory immediately	pH/Ion-meter	Water quality - Determination of pH (ISO 10523:2008)
Electro conductivity	Refrigerator	Laboratory immediately	Conduct-meter	Water quality -- Determination of electrical conductivity (ISO 7888:1985; ISO/TC 147/SC 2)
Total solids (TS), Total volatile solids (TVS), Total fixed solids (TFS) Total suspended solids (TSS)	Refrigerator	Laboratory - up to 24h	Filter	Standard Methods for the Examination of Water and Wastewater, Lenore S. Clesceri, Arnold E. Greenberg, Andrew D. Eaton, 1999 by American Public Health Association, American Water Works Association, Water Environment Federation, 20th Edition
Chemical oxygen demand (COD)	Acidification with H_2SO_4 up to pH 1-2	Laboratory - up to 1 month		Serbian method P-IV-10 Q5-04-450
Biological oxygen demand (BOD_5)	Refrigerator	Laboratory - up to 1 month	Oximeter	Water quality - Determination of biochemical oxygen demand after n days (BODn) - Part 2: Method for undiluted samples (ISO 5815:1989, modified to 2:2009)
Total nitrogen (N_{tot})	Acidification with H_2SO_4 up to pH 1-2	Laboratory - up to 1 month	Analyser for carbon and nitrogen	Water quality - Determination of nitrogen - Determination of bound nitrogen (TNb), following oxidation to nitrogen oxides EN 12260:2008
Ammonium- Nitrogen (NH_4-N)	Refrigerator	Laboratory - up to 21 days	Spectrophometer	SRPS EN ISO 11905 - 1:2009
Nitrate - Nitrogen (NO_3-N)	Acidification with HCl up to pH 1-2	Laboratory - up to 7 days	Spectrophometer	SRPS EN ISO 10304 - 1:2009
Total phosphorous (P_{tot})	Acidification with H_2SO_4 up to pH 1-2	Laboratory - up to 1 month	Spectrophometer	SRPS EN ISO 6878:2008

3.3.1.4 Evaluation of Measured Data

3.3.1.4.1 Wastewater Flow

The mean annual wastewater flow ($Q_{ww,aM}$) is calculated as a sum of domestic and industrial wastewater flow (Equation 3.1):

$$\mathrm{Qww, aM = QDom, aM + QInd, aM} \qquad (3.1)$$

Domestic wastewater flow ($Q_{Dom,aM}$) is derived from the drinking water consumption rate and population connected to sanitation services. To determine the consumption rate, data from the previous seven available years (2005-2012) was provided by the PUCs. Given that no outstanding consumption trends were evident, the consumption rate as assigned that from the most recent available year (2012). Industrial wastewater flow ($Q_{Ind,aM}$) was determined from the water consumption rate of the industry, reduced by an assumed 10% water utilisation for production processes. Given that no measurements of industrial water use exist, the assumption of 10% was used because a major part of the industry consists of food and dairy production, which means that some part of the consumed water remains bound in the products.

The daily dry weather flow ($Q_{DW,pM}$) for an observed period was calculated as a mean of daily flows (Q_d) recorded on dry weather days. Dry weather is considered a day on which, or the previous day, precipitation ≤ 1mm (ATV-DVWK-A, 198). Plausibility was checked using the "night minimum" method. Thus, recorded flows in the early morning hours from Saturdays to Mondays (1 a.m. - 6.a.m) were evaluated. The results of both methods indicate similar results.

Infiltration water ($Q_{Inf, pM}$) was derived from Equation 3.2:

$$\mathrm{QInf, pM = QDw, pM - Qww, aM} \qquad (3.2)$$

3.3.1.4.2 Wastewater Pollutants Loads

Based on the measured wastewater flow and pollutant concentrations, daily loads (L_d) were calculated with Equation 3.3:

$$\mathrm{L_d}\left[{}^{\mathrm{g}}/_{\mathrm{day}}\right] = \frac{\mathrm{c_d}\left[{}^{\mathrm{mg}}/_{\mathrm{l}}\right] \cdot \mathrm{Q_d}\left[{}^{\mathrm{m^3}}/_{\mathrm{d}}\right]}{1000} \qquad (3.3)$$

where C_d is a daily pollutant concentration based on 24-hr composite sample and Q_d is the corresponding daily flow. If referring to one person, the pollutant load produced during one day is called “inhabitant-specific” or “person load” and the unit used is g/(cap*d). Calculation of the inhabitant-specific loads is based on the following Equation (3.4):

$$L\left[{}^{\mathrm{g}}/_{(\mathrm{cap} * \mathrm{d})}\right] = \frac{\mathrm{L_{d\ 85\%\ fractile}}\left[{}^{\mathrm{g}}/_{\mathrm{d}}\right]}{\text{Population (n) with access to the sewer netwok}} \qquad (3.4)$$

3.3.2 Surveys

In the scope of the research three surveys were administered for data collection: 1) Industrial Wastewater Survey; 2) Bio-Waste Survey; 3) Agro-Waste Survey.

3.3.2.1 Industrial Wastewater Survey

To better understand the influence of industrial wastewater on overall wastewater quality, industrial activities in the CSR were analysed. First, industries in the CSR which discharge their wastewater into the sewer were identified through records provided by Waterworks Stara Pazova and Waterworks Indjija. Second, a survey was planned and administered to the companies. The survey included questions related to production, capacity, operation regime and effluent quantities (Appendix 1). In total, 123 industries were identified, of which 93 participated; as some of these were incomplete, results from 76 surveys were included in the analysis (Appendix 1). The survey was announced via telephone to each company, and then the questionnaire was sent via e-mail. The largest 17 companies were personally visited in September 2014, with the survey administered at the visits. The companies which most often refused to participate in the survey included mainly meat and dairy processors.

3.3.2.2 Bio-Waste Flow Survey

In accordance with the Serbian Waste Management Law ("RS Official Gazette" No. 36/09), the Law of Self Government ("RS Official Gazette" No. 129/07) and the Law of Public Utility Service ("RS Official Gazette" No. 42/98), local governments are responsible for waste management at the municipal level. Therefore, data on bio-waste flows (including kitchen waste, green cut, and industry-organic waste) were initially collected from existing municipal records and state statistical records. Due to inconsistencies between the two data sources, a Waste Management Survey was developed and administered (Appendix 2). The survey set out to assess waste generation trends in Stara Pazova municipality over the past 10 years. The survey consisted of seven questions requesting monthly base data for the period 2003-2012. The questionnaire was submitted via e-mail to PUC Stara Pazova and the requested information was discussed with PUC representatives in September 2013. Based on consultations, the PUC completed and returned the survey.

3.3.2.3 Agro-Waste Survey

The most challenging data to collect was estimates of the available biomass from the agricultural sector in Stara Pazova. More precisely, data on crop area and yield cited by state statistical records did not agree with that of the National Treasury. Data on livestock production was missing for most years of the analysed time. The survey intended to fill these gaps.

The municipality of Stara Pazova has ca. 30,000 ha of agricultural land with many farms; therefore, a sample population of farmers was identified in cooperation with the Department for Agriculture and Rural Development of Stara Pazova. The survey sample included 22 farms covering 65% of the available agricultural area and all settlements (Fig. 3.4). The aim of the survey was to estimate available bio-waste matter from the agriculture sector. The data on the harvested area (ha) and crops yields for 2002-2012 were collected and summarised in an Excel spreadsheet.

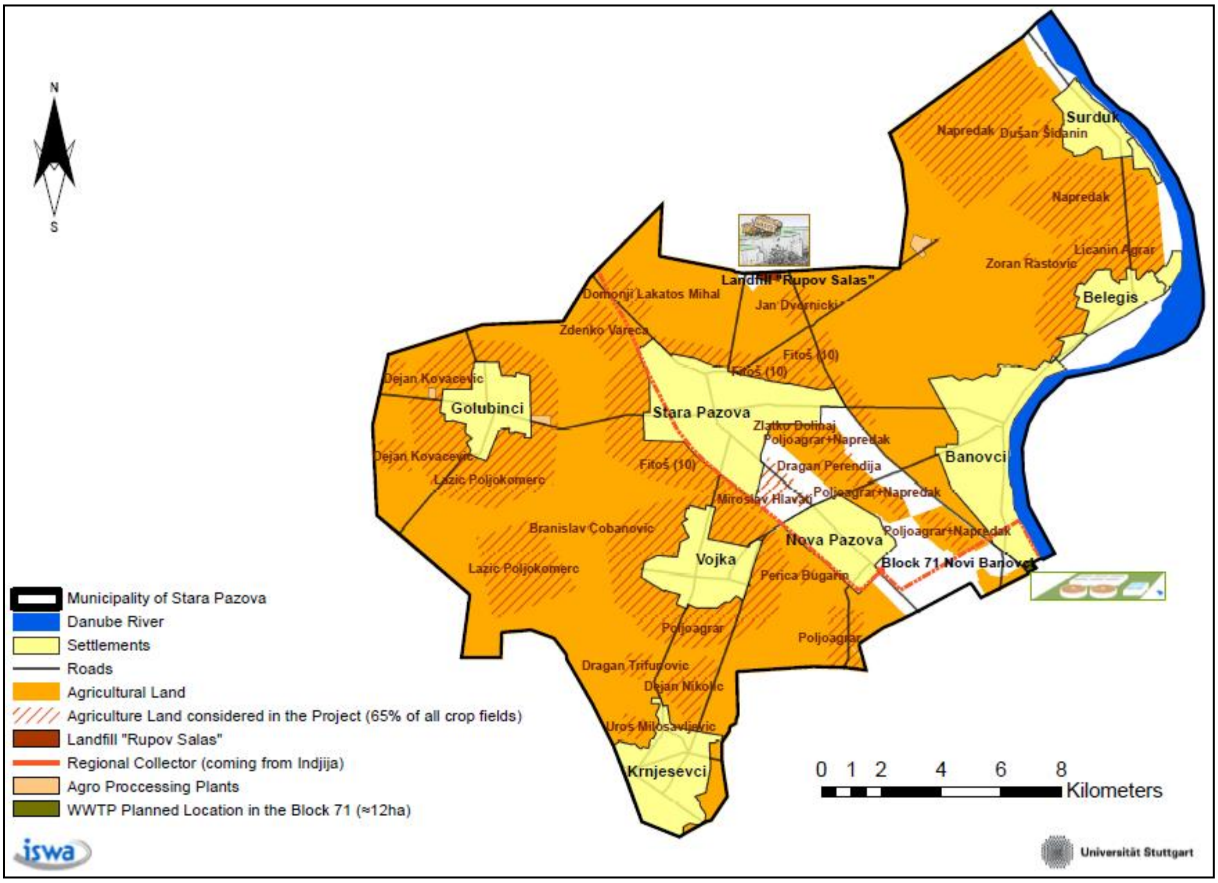


Fig. 3.4: Bio-mass survey sample locations.

The survey (Appendix 3) included the following:

- Area of crops and yields;
- Number of animals, their weight and the average age of each animal, and type of the manure (solid/liquid);
- Current treatment and disposition of agriculture biomass residue and manure (e.g., buried, burned, animal feed, bedding);
- Percentage of biomass residue/manure currently used for own needs;
- Percentage of biomass that farmers are willing to provide for energy production.

To facilitate survey participation, all 22 farm households were personally visited with the representatives of Stara Pazova and interviewed in September 2013. Since the amount of agriculture biomass is highly volatile and seasonal, depending on weather, markets and other factors, it is crucial to accurately evaluate potentially obtainable flows for anaerobic digestion. For the mass balance and energy estimates, 95% confidence interval for the period 2003-2012 was used. A mass balance was performed to determine the amount of fermentation residues (based on given substrate inputs) outputted from the anaerobic digestion.

3.3.3 The Decision Support Tool

The DST, developed in Microsoft Excel, consists of three main parts: 1) integrated scenario development, 2) graphical presentation of results, and 3) comparative scenario assessment (Fig. 3.1).

3.3.3.1 Starting Assumptions

Since there are numerous technologies for wastewater treatment and energy and nutrient recovery, the following assumptions were established for this research:

- Given that the Activated Sludge Process (ASP) is the most commonly applied wastewater treatment technology worldwide, WWTP scenarios are based on ASP with pre-denitrification, gravity thickening and mechanical dewatering (centrifuge) of sewage sludge.
- For one decentralized treatment facility, one conventional technology, a SBR, and one natural-based technology CW has been selected
- As anaerobic digestion is consistent with ASP, this energy recovery technology was selected. Generated biogas is burned in combined-heat-and-power (CHP) unit and transferred into electrical and heat energy.
- For effluent recovery, UV disinfection is assumed
- For phosphorus recovery, MAP production based on Stuttgart process is assumed.

3.3.3.2 Integrated Scenarios Development

As shown in Tab. 3.5, the DST calculates the potential of energy generation (electrical and heat), phosphorus recovery and wastewater re-use for sixteen different integrated scenarios based on user-determined processing options, plus make a comparison of centralized versus decentralised options. Based on user selections for phosphorus recovery and water re-use, the scenarios are arranged in four categories (Tab. 3.5):

- Type “a”: Neither wastewater re-use nor phosphorus recovery.
- Type “b”: Wastewater re-use; no phosphorus recovery.
- Type “c”: Phosphorus recovery; no wastewater re-use.
- Type “d”: Both wastewater re-use and phosphorus recovery

For each scenario, users can also select centralized or decentralised wastewater treatment variants (Tab. 3.5). Scenarios Type 1 are centralized concepts; Type 2 consider SBR but not CW; Type 3 consider CW but not SBR; and type 4 consider both CW and SBR.

Tab. 3.5: Scenarios of the DST.

			Wastewater reuse	Phosphorus recovery	Wastewater reuse	Phosphorus recovery	Wastewater reuse	Phosphorus recovery	Wastewater reuse	Phosphorus recovery
SBR	CW		no	no	yes	no	no	yes	yes	yes
			a		b		c		d	
no	no	1	Scenario a-1		Scenario b-1		Scenario c-1		Scenario d-1	
yes	no	2	Scenario a-2		Scenario b-2		Scenario c-2		Scenario d-2	
no	yes	3	Scenario a-3		Scenario b-3		Scenario c-3		Scenario d-3	
yes	yes	4	Scenario a-4		Scenario b-4		Scenario c-4		Scenario d-4	

The DST furthermore evaluates for each scenario, two Variants:

- Variant 1 (Fig. 3.5): A single, conventional, centralized WWTP and one digester.

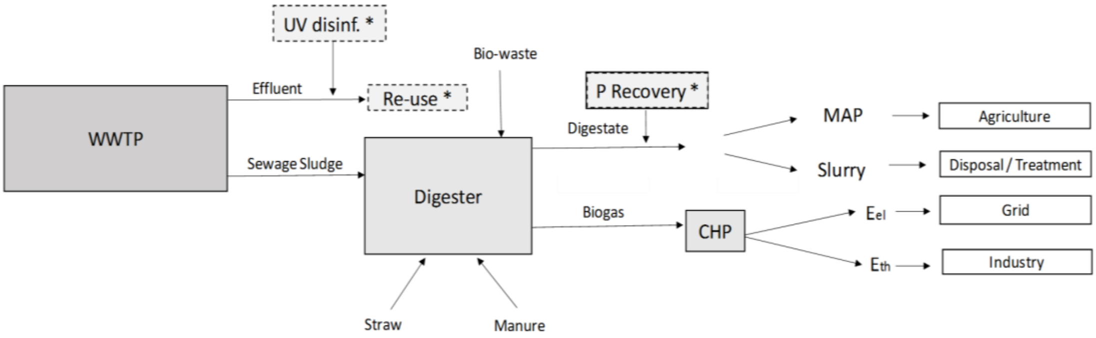


Fig. 3.5: Variant 1 (centralised) of the DST (optional add-ins and based on user preference).*

- Variant 2 (Fig. 3.6): Modular approach with options for decentralised wastewater treatment (SBR and/or CW) for rural communities and two separate digesters: Digester 1 for flows originating from wastewater and solid waste sectors (where contaminants are a concern) and Digester 2 for “clean” waste flows from the agriculture sector.

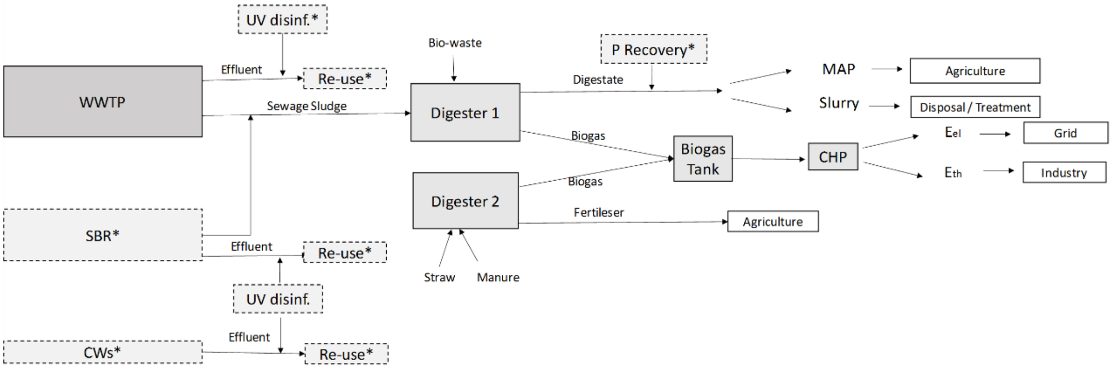


Fig. 3.6: Variant 2 (decentralised) of the DST (* optional add-ins and based on user preferences).

Using the DST, there are three steps to scenario development (Fig. 3.7). Step 1 includes “User Input Selection” and “User Input Flow”. Based on Step 1 data, in Step 2 the DST computes the mass balance and energy production (Step 2a); and MAP, water and energy recovery potential (Step 2b). The results of Steps 1 and 2 are then inputted for the financial analysis in Step 3.

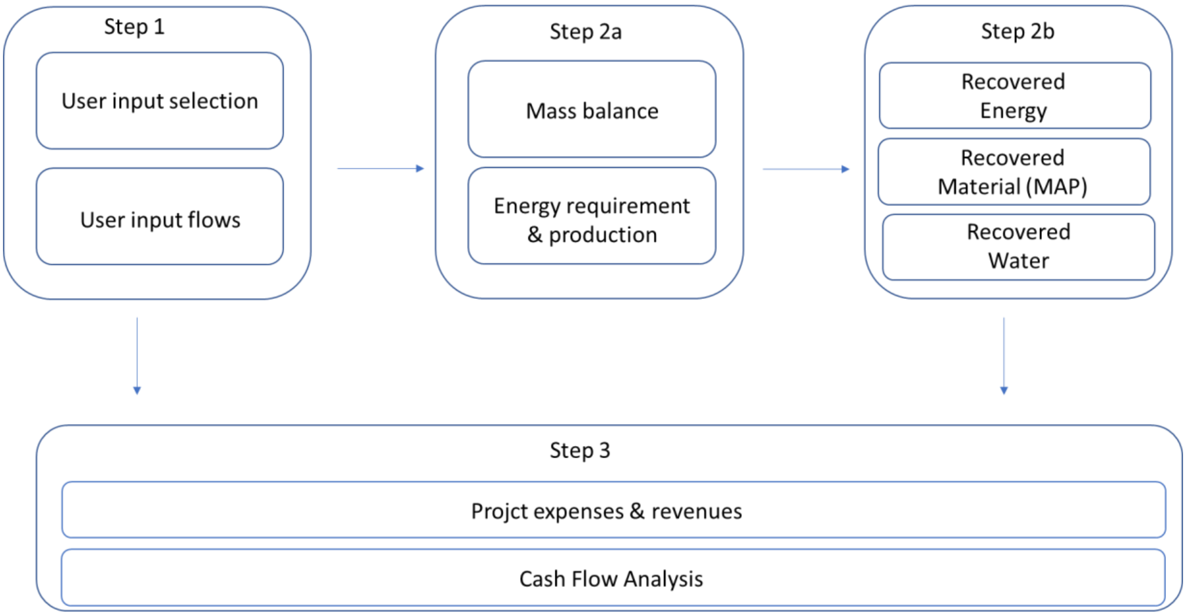
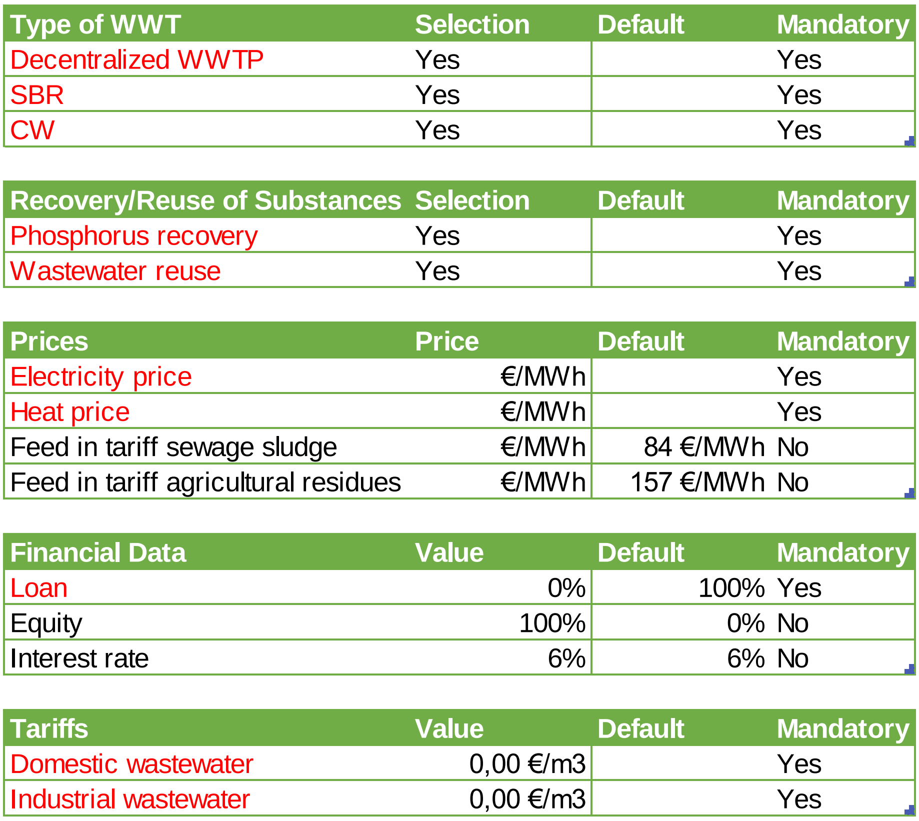


Fig. 3.7: Integrated scenario development used for DST.

3.3.3.2.1 Scenario Development Step 1

Once the tool opens in Excel, the first worksheet (tab) the user sees is “User Input Selection” (Fig. 3.7), containing mandatory fields (marked red in Fig. 3.8) concerning the following:

- **Type of Wastewater Treatment (WWT):** Users can select partly decentralized wastewater treatment; this option is mandatory. If decentralized wastewater treatment is marked “Yes”, then users can choose between the options “SBR” (Sequence Batch Reactor) and/or “CW” (Constructed Wetland). If “No” is marked, “SBR” and “CW” options are deactivated.
- **Recovery/Reuse of Substances:** This mandatory entry requires the user to select options for wastewater and phosphorus recovery.
- **Prices, Financial Data & Tariffs:** Users enter prices of utilities, commodities, tariffs, and financing terms in the respective sections. For non-mandatory fields, if the user does not specify, the tool enters default values.



Type of WWT	Selection	Default	Mandatory
Decentralized WWTP	Yes		Yes
SBR	Yes		Yes
CW	Yes		Yes

Recovery/Reuse of Substances	Selection	Default	Mandatory
Phosphorus recovery	Yes		Yes
Wastewater reuse	Yes		Yes

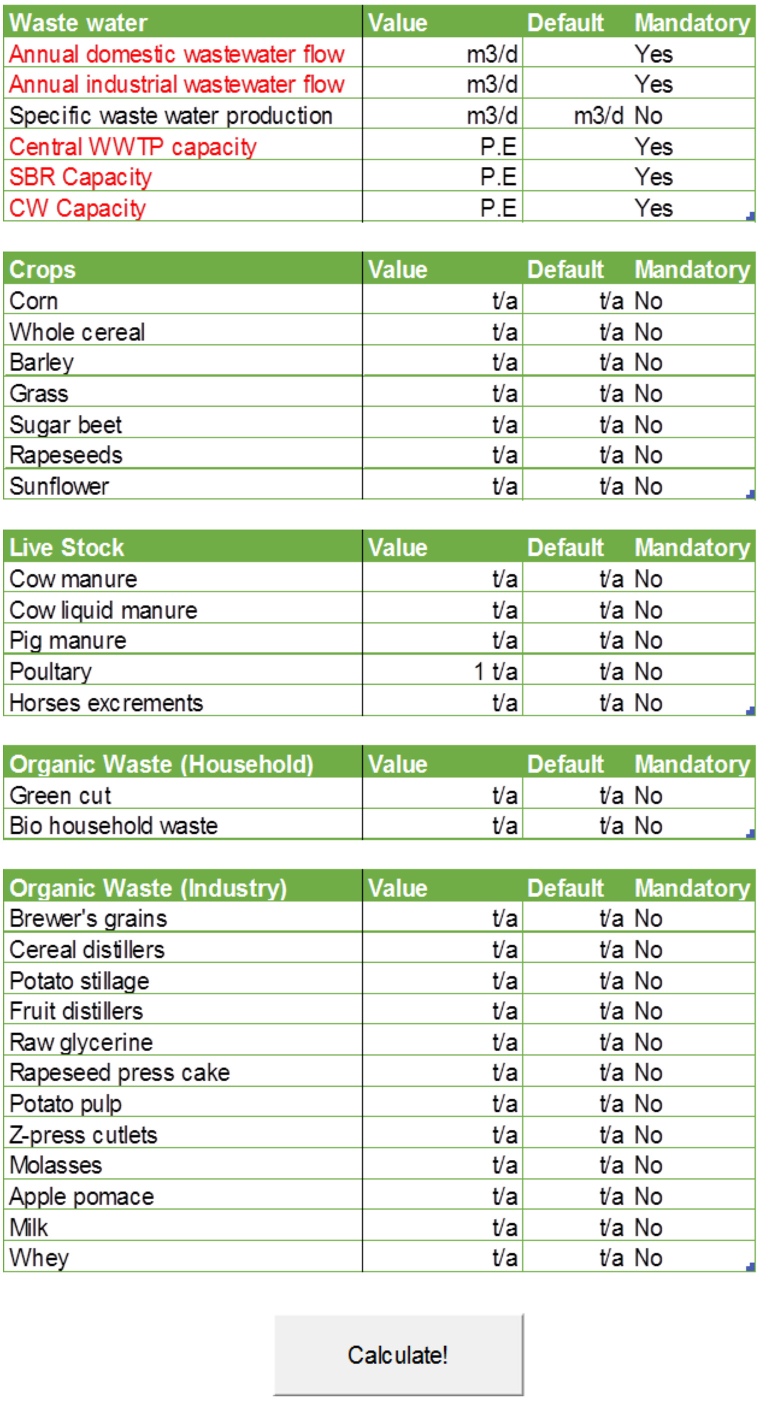
Prices	Price	Default	Mandatory
Electricity price	€/MWh		Yes
Heat price	€/MWh		Yes
Feed in tariff sewage sludge	€/MWh	84 €/MWh	No
Feed in tariff agricultural residues	€/MWh	157 €/MWh	No

Financial Data	Value	Default	Mandatory
Loan	0%	100%	Yes
Equity	100%	0%	No
Interest rate	6%	6%	No

Tariffs	Value	Default	Mandatory
Domestic wastewater	0,00 €/m3		Yes
Industrial wastewater	0,00 €/m3		Yes

Fig. 3.8: DST, Step 1 - “User input selection”

In the next step, “User Input Flows”, users enter requested flows, as shown in Fig. 3.9; mandatory fields are again marked in red. For non-mandatory fields, non-entries will be assigned a default value or “0”. When the user clicks “Calculate” Excel then checks for mandatory entries and completes the calculates.



Waste water	Value	Default	Mandatory
Annual domestic wastewater flow	m3/d		Yes
Annual industrial wastewater flow	m3/d		Yes
Specific waste water production	m3/d	m3/d	No
Central WWTP capacity	P.E		Yes
SBR Capacity	P.E		Yes
CW Capacity	P.E		Yes

Crops	Value	Default	Mandatory
Corn	t/a	t/a	No
Whole cereal	t/a	t/a	No
Barley	t/a	t/a	No
Grass	t/a	t/a	No
Sugar beet	t/a	t/a	No
Rapeseeds	t/a	t/a	No
Sunflower	t/a	t/a	No

Live Stock	Value	Default	Mandatory
Cow manure	t/a	t/a	No
Cow liquid manure	t/a	t/a	No
Pig manure	t/a	t/a	No
Poultary	1 t/a	t/a	No
Horses excrements	t/a	t/a	No

Organic Waste (Household)	Value	Default	Mandatory
Green cut	t/a	t/a	No
Bio household waste	t/a	t/a	No

Organic Waste (Industry)	Value	Default	Mandatory
Brewer's grains	t/a	t/a	No
Cereal distillers	t/a	t/a	No
Potato stillage	t/a	t/a	No
Fruit distillers	t/a	t/a	No
Raw glycerine	t/a	t/a	No
Rapeseed press cake	t/a	t/a	No
Potato pulp	t/a	t/a	No
Z-press cutlets	t/a	t/a	No
Molasses	t/a	t/a	No
Apple pomace	t/a	t/a	No
Milk	t/a	t/a	No
Whey	t/a	t/a	No

Fig. 3.9: DST, Step 1 - “User input flows”

3.3.3.2.2 Scenario Development Step 2

In Step 2 (Fig. 3.7), the mass balance of sewage sludge and other organic flows is performed. Sewage sludge quantities (WWTP and, if applicable, SBR) is calculated based on the procedure of the technical norm ATV-DVWK-A 131E, (ATV, 2000). For this research mass balance input parameters derived from the results of the wastewater measuring campaign were used (BOD_5= 85 g/(PE*d), COD=155 g/(PE*d), TSS= 90 g/(PE*d), N_{tot}=14 g/(PE*d), P_{tot}=11 g/(PE*d); further details Chapter 4.1.1.5). Energy co-production and requirements were calculated based on standard literature sources. All main assumptions and unit values used for mass balances and energy calculations are listed in Appendix 4.

3.3.3.2.3 Scenarios Development Step 3

Step 3 – Economic Analysis (Fig. 3.7) data is acquired from Steps 1 and Step 2. The Economic Analysis consists of a Cost Benefit Analysis (Tab. 3.6) and Net Present Value (NPV). The Cost Benefit Analysis was incorporated as outlined by the Water Framework Directive 2000/60/EC. As Tab. 3.6 summarizes, project expenses include investment, operational and maintenance costs. The investment costs of applicable treatment units (e.g., WWTP, SBR, CW, nutrient recovery, disinfection) are calculated based on capacity/size and other specific costs. Operational costs are based on outcome on the mass balance results (Step 2) and other specific costs (Appendix 5). Operation costs (Tab. 3.6) include labour, electricity, MAP recovery, effluent disinfection, digestate transport & disposal, chemicals, and maintenance. Literature data, feasibility studies, and interviews with plant operators was used to derive mandatory values for investment, operation and maintenance. All values used are presented in Appendix 5. Maintenance costs are set at 2% of the total annual operation costs. Revenues include co-generation savings and outputs (e.g., electricity, thermal energy, MAP) and wastewater tariffs. Gate fee for bio-waste treatment was not included into cost benefit analysis. For slurry only disposal as a treatment option was considered. Although brining positive added value, revenues from wastewater reuse not included in cost benefit analysis.

Tab. 3.6: Cost Benefit Analysis used in the DST.

Expenses	Investment Costs	Wastewater treatment WWTP
		Wastewater treatment SBR
		Wastewater treatment CW
		Digester 1
		Digester 2
		MAP Recovery
		Effluent disinfection WWTP
		Effluent disinfection SBR
		Effluent disinfection CW
	O & M Costs	Labor
		Electrical Energy - wastewater treatment & digester
		MAP Recovery
		Effluent disinfection WWTP
		Effluent disinfection SBR
		Effluent disinfection CW
		Transport & disposal of slurry
		Chemical costs
		Maintenance
Revenues		Generated electricity
		Generated heat
		MAP Recovery
		Digestate digester 2
		Income wastewater tariffs

The financial analysis was been performed by the mean of Cash Flow Analysis method. The following Equation (3.5) is used to calculate Net Present Value (NPV).

$$NPV = \sum_{t=}^{n} \frac{R_t}{(1+i)^t} \tag{3.5}$$

Where:

R_t = Net cash inflow-outflow during a single period,
i = Discount rate or return,
t =Number of time periods.

The annuity factor includes rate of interest (user-set, or default 5%) and depreciation period of the plant component, set to 20 years.

3.3.3.3 Graphical Presentation

Based on user preferences (Fig. 3.8) the DST calculates one of 16 possible scenarios (Tab. 3.5) and schematically presents the mass flow and financial projections for the two variants (Fig. 3.5, Fig. 3.6).

3.3.3.4 Comparative Scenarios Assessment

The DST thus allows decision-makers to run rapid comparative analyses of two variants of the user specified scenario. The assessment consists of five main criteria subdivided into twenty sub-criteria (Tab. 3.7). Qualitative evaluation, was made based on literature consideration (DWA; 2014). Quantitative parameters are derived from mass and energy balances and financial analysis.

Tab. 3.7: List of criteria and sub-criteria used for comparative scenarios assessment. Source: Modified from Bertanza et al., 2018) and DWA, 2014

Criterion	No.	Sub-criterion	Type	Measurement unit
1 Technical	1.1	Flexibility/modularity	Qualitative	-
	1.2	Operational complexity	Qualitative	-
	1.3	Process stability & Robustness	Qualitative	-
	1.4	Infrastructure adaptation	Qualitative	-
2 Social	2.1	Public acceptance	Qualitative	-
	2.2	Employment Opportunities	Qualitative	-
3 Environmental	3.1	Landfilled residues	Quantitative	t/a
	3.2	Energy consumption	Quantitative	kWh/a
	3.3	Reagens consumption	Quantitative	t/a
	3.4	GHGs emissions	Quantitative	t CO_{2eq}/a
	3.5	Recovered energy	Quantitative	t/a
	3.6	Recovered materials	Quantitative	t/a
	3.7	Re-used water	Quantitative	m^3/a
4 Financial	4.1	Investment Costs	Quantitative	€
	4.2	O&M Costs	Quantitative	€/a
	4.3	Revenues	Quantitative	€/a
	4.4	NPV	Quantitative	€
5 Administrative	5	Complexity of authorisation	Qualitative	-

3.3.3.4.1 Technical Aspects

Technical Aspects include four sub-criteria (Tab. 3.7): Flexibility/Modularity, Operational Complexity, Process Stability & Robustness, and Infrastructure Adaptation.

Flexibility/Modularity (1.1): Addresses the adaptability and expandability of the technology to changing conditions such as abatement limits, legal requirements, climate change, demographic changes, and possibility of modular upgrade or downgrade to meet changing needs.

Operational Complexity (1.2): Level of operation complexity is important when balancing treatment technology with local labour-market skills. The need for labour capacity and training should be considered.

Process Stability & Robustness (1.3): Denotes system durability and resilience to potential changing future conditions. Seasonal variations in wastewater and organic flow rates and compositions can significantly influence process operations; potential consequences are also accounted for. In a decentralised concept, system failure may be less damaging than in a centralized system.

Infrastructure Adaptation (1.4.): Ability of the system to adapt proposed technology to existing infrastructure, as well as further improvements such as energy and nutrient recovery, water reuse or renewable energy production.

3.3.3.4.2 Social Aspects

Social Aspects addresses three sub-criteria (Tab. 3.6): Affordability, Public Acceptance and Employment Opportunities.

Public Acceptance (2.1): Acceptance by communities and users of new processes and infrastructure. The following factors can influence public acceptance: location, aesthetics, odour, traffic and logistics.

Employment Opportunities (2.2): Evaluates new employment opportunities generated for construction and operation.

3.3.3.4.3 Environmental Protection

Environmental Protection includes seven sub-criteria (Tab. 3.6): Landfilled Residues, Energy Consumption, Reagents Consumption, GHG Emissions, Recovered Energy, Recovered Materials and Re-Used Water.

Landfilled Residues (3.1.): Amount of non-usable digestate (e.g., due to impurities) that has to be landfilled.

Energy Consumption (3.2): Energy requirement for the treatment processes, including electricity for pumping, filtration, lifting equipment and other operations.

Reagents Consumption (3.3): Substances necessary for treatment process such as precipitation, flocculation and dewatering.

GHGs Emissions (3.4): GHGs emissions result from fossil fuel energy supplied to system reactors (WWTP, digester), plus emissions from treatment operations (notably N_2O emissions from nitrification and denitrification process and CH_4 from WWTP and anaerobic digestion occurring in the sewer system). GHG emissions from transport of bio-waste flows were not considered in this research.

Recovered Energy (3.5): Net energy recovery in the form of biogas.

Recovered Materials (3.6): Recovery of phosphorus as a finite element.

Re-Used Water (3.7): Amount of wastewater to be re-used by the process.

3.3.3.4.4 Financial Aspects

Financial Aspects consists of four sub-criterion (Tab. 3.6): Investment Costs, O&M Costs, Revenues, and NPV.

Investment Costs (4.1): Capital investment required to construct the treatment process and infrastructure. Since local administrations are responsible for treatment, this is of great importance to decision-makers.

O&M Costs (4.2): Proper operation and maintenance help ensure continued safe, effective plant operation. These expenses are generally passed on to consumers through tariffs.

Revenues (4.3): Financial benefits from energy reutilized on site, thermal energy delivered to industrial users, electrical energy supplied to the grid, and/or sale or trade of recovered minerals and materials for the agricultural sector.

Net Present Value (NPV) (4.4): Assessment of the long-term profitability of the project, calculated by summing all the revenues over the life, minus all expenses, and discounted by an appropriate rate.

3.3.3.4.5 Administrative Aspects

Complexity of Authorisation (5.1): Administrative processes of issuing permits and authorizations for emissions, safety standards, certifications and other requirements.

4 Results and Discussion

4.1 Results of Mass Flows Analysis

4.1.1 Wastewater Sector

4.1.1.1 Wastewater Flow

Fig. 4.1 shows measured daily wastewater flows (line graph, m^3/d), together with measured precipitation (data points, mm) for the defined sewer catchment area. As Serbia experienced severe flooding from May 10-25, 2014 and in order to understand the wastewater flow dynamic, the Fig. 4.1 includes measurements from prior to the flooding (April 1 through June 6, 2014). The wastewater flow measurements recording during the measurement campaign conducted in the scope if this research beginning with the vertical dotted line in Fig. 4.1. As mentioned in Chapter 3.2, the sewer catchment area for the recorder flows covers ca. 42,000 inhabitants (37% of the total CSR population) and almost all existing industry and commercial units.

As seen in Fig. 4.1, prior the flooding, in April, rain events generally led to increased daily wastewater flows. However, a significant leap in wastewater flow is observed beginning on May 14, just several days after the intense rains began. During the flooding, the highest precipitation was recorded on May 14, with 138 mm/day, causing the maximum recorded daily wastewater flow 30,400 m^3/d on May 18. In comparison with the period prior to the flood, the increased flows continued for four months after flooding subsided; the first indicated decrease of wastewater flow is observed at the end of June. Notable daily variations and overall increased flows are observed in July and August. One reason for this is the obvious influence of precipitation on flow (infiltration). During the measurement campaign (June 17 through December 7), the average daily flow on days with precipitation ($Q_{d,av,pM}$= 16,100 m^3/d) was higher than the average dry-weather flow ($Q_{DW,av,pM}$=15,000 m^3/d, Tab. 4.1); thus, we can conclude that the increased daily wastewater flows in summer are caused at least in part by rainwater infiltration.

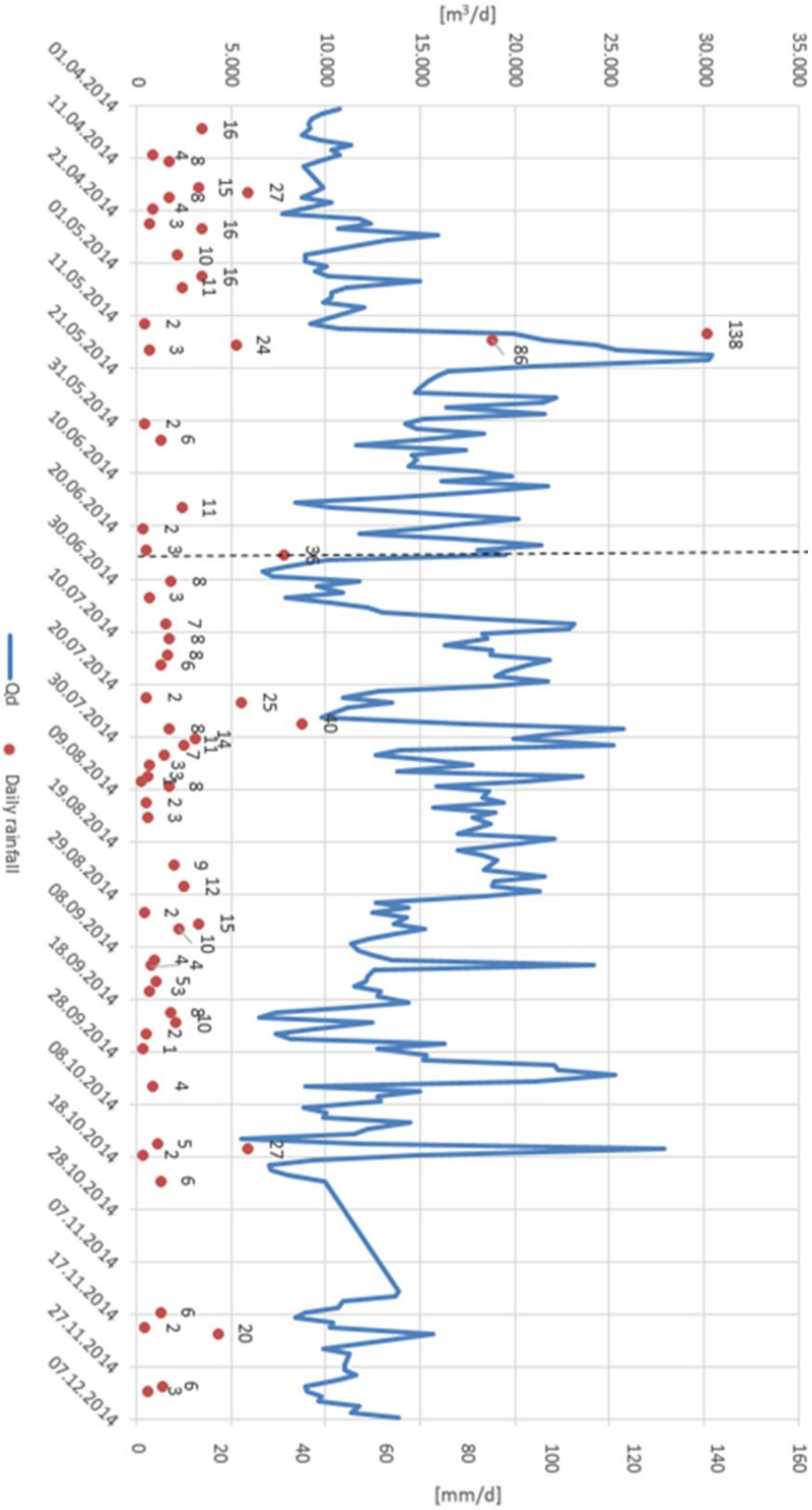


Fig. 4.1: Recorded daily flows (m^3/d) and precipitation (mm/d), PS1: 01.04 – 07.12.2014.

Contributions from industrial wastewater are a second likely reason for the increased wastewater flows in summer, at least in part to significantly increased wastewater discharge from an ice-cream producer. The Industrial Wastewater Survey (Appendix 1), revealed that the annual capacity of the ice-cream producer 22,500 t of ice-cream, and it is the greatest wastewater contributor with 53,000 m^3/a. In the summertime, peak production is achieved: 1,300 t/month in June and 1,000 t/month in July. In August, production drops to 300 t/month which consequently causes a decrease of wastewater which can be observed in Fig. 4.1.

Our survey also revealed the second-highest generator is from metal processing companies (ca.16,000 m^3/a) and dairies (ca. 10,000 m^3/a). The five largest meat producers annually generating ca. 30,000 m^3 wastewater. In Stara Pazova there is a beverage company discharging wastewater of ca. 1,000 m^3/a, plus small dairies generating in total 1,500 m^3/a wastewater. Most of the meat and dairy processing companies in Stara Pazova collect generated wastewater in septic tanks, as they lack wastewater treatment processes. Septic tanks are emptied by the public utility company or one of several private companies in a truck cistern (5m^3). This collected wastewater is discharged to the Danube River at one of many unofficially regulated locations in the municipality. Depending on the production levels, the meat companies alone require between 200 to 2,400 discharge rounds annually. Based on personal interview with the biggest companies, it is assumed that most of these illegal discharges are made before the PS-1. This explains some of the recorded seasonal variations, especially notable trends at the beginning and middle of September and October.

Fig. 4.2. presents recorded dry wastewater flows (flows on days without precipitation) during the measurement campaign. As observed, the decreased wastewater flow is obvious on weekends, following weekly maximums often on Thursdays and/or Fridays. This can be explained by the end-of-week production processes and cleaning.

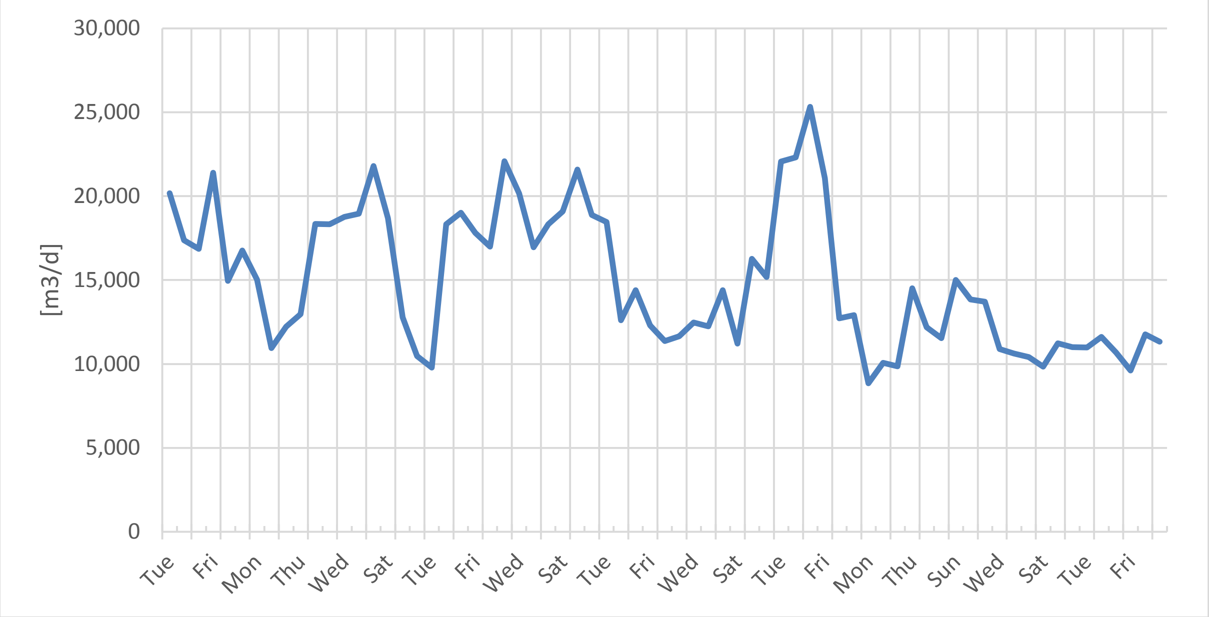


Fig. 4.2: Daily dry weather flow (m^3/d), PS1: 17.06 – 07.12.2014.

Based on collected data and the results of the measurement campaign, Fig. 4.3 summarises the annual wastewater balance for the CSR. The CSR generates 6.8 M m^3 of municipal wastewater annually, of which 41% is evacuated by the collector, resulting in annual wastewater flow $Q_{WW,aM}$ = 2.78 Mil.m^3/a (7,667 m^3/d). The flow consists of 77% domestic wastewater (2.1 Mil.m^3/a) and 23% pre-treated industrial wastewater (0.65 Mil.m^3/a). The difference of 4.0 Mil.m^3/a is household wastewater discharged directly to the Danube or collected in septic tanks (and then later dumped into the Danube).

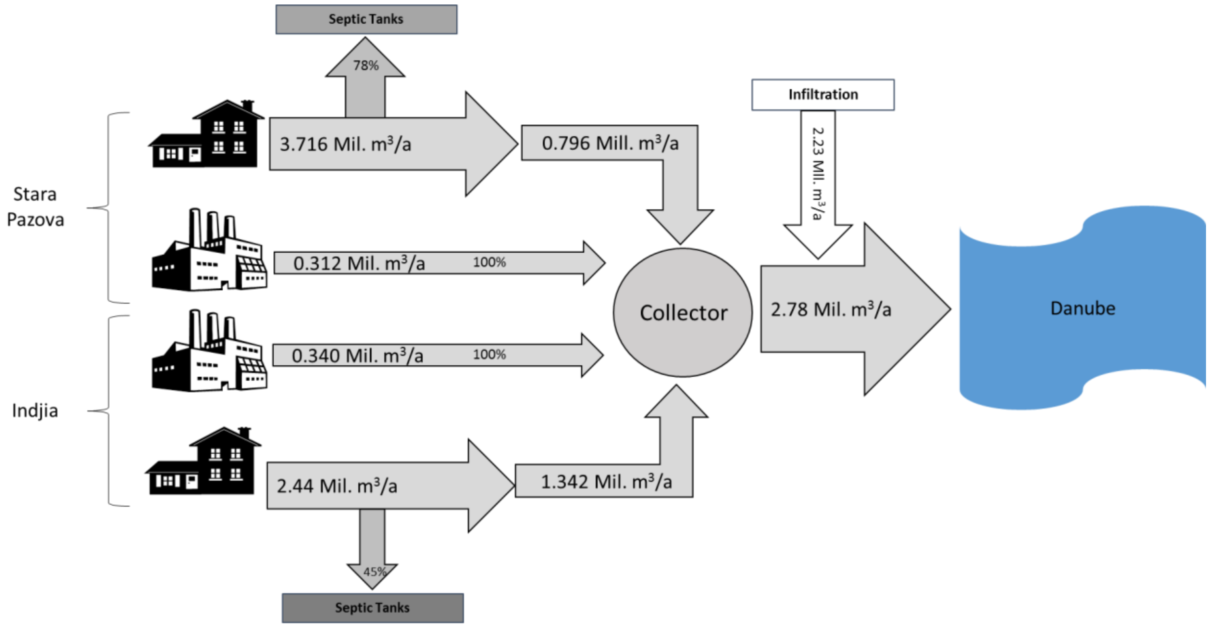


Fig. 4.3: Wastewater balance of the CSR, 2014.- status quo situation.

Tab. 4.1 summarizes the CSR's daily wastewater flow data per municipality and the overall CSR based on the connected population (2014).

Tab. 4.1: Case Study Region wastewater data for the connected population, 2014.

	Access to sewer system	Inhabitant specific water consumption	$Q_{Dom,aM}$	$Q_{Ind,aM}$	$Q_{WW,aM}$
	(Inhabitants)	(l/(cap*d))	(m^3/d)	(m^3/d)	(m^3/d)
Indjija	26,400	140	3,696	933	4,629
Stara Pazova	14,950	146	2,183	855	3,038
CSR	41,350	142	5,879	1,788	7,667

The daily dry-weather flow ($Q_{DW,d,pM}$) for the observed period during measurement (June 17 – December 7, 2014) was taken as the mean of the recorded flows on dry weather days[2], resulting in 15,000 m^3/d (Tab. 4.2). Infiltration (calculated from Equation 3.2) accounts for an estimated 50% of dry weather flow ($Q_{Inf}=42\%Q_{DW}$), or 96% of the wastewater flow ($Q_{Inf}=82\%Q_{WW}$). The daily average wastewater flow ($Q_{D,av,pM}$) for the observed period was 14,570 m^3/d.

---

[2] A dry weather day means precipitation of ≤ 1mm both on the same day and on the previous day (ATV,2000).

Tab. 4.2: Case Study Region calculated wastewater data for the connected population based on measurement campaign (rounded to 42,000 inhabitants).

	$Q_{DW,d,pM}$	$Q_{DW,pM,max}$	$Q_{DW,pM,min}$	$Q_{Inf,pM}$	$Q_{D,av,pM}$
	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)	(m^3/d)
17.06 - 06.12.2014	15,000	25,330	8,840	6,334	14,570

4.1.1.2 Physical Parameters

The monitoring campaign measured and recorded the following physical parameters: temperature, electro-conductivity and pH.

The average recorded air temperature was 13°C, with a minimum of 0°C and maximum of 28°C (median 15°C). The average measured wastewater temperature was 23°C, with a minimum of 17°C and maximum of 29°C (Fig. 4.4).

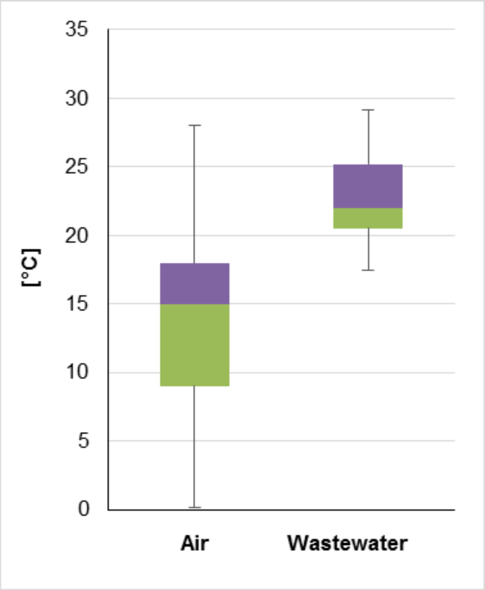


Fig. 4.4: Measured air and wastewater temperatures, PS1: 17.06 - 06.12.2014 (101 samples).

Fig. 4.5 presents measured conductivity values; conductivity was in the interquartile range of 1,500-1,700 µS/cm (median 1,600 µS/cm, and extremes reaching 4,000 µS/cm). Average conductivity was 1,625 µS/cm. The Serbian Decree on Pollutant Emission Limit Values does not establish surveillance values for conductivity, making illegal industrial wastewater discharges difficult to spot. Increased electro-conductivity can also corrode sewage pipes, so industrial wastewaters discharged into the municipal sewer network are limited to 5,000 µS/cm (Levlin, 2010).

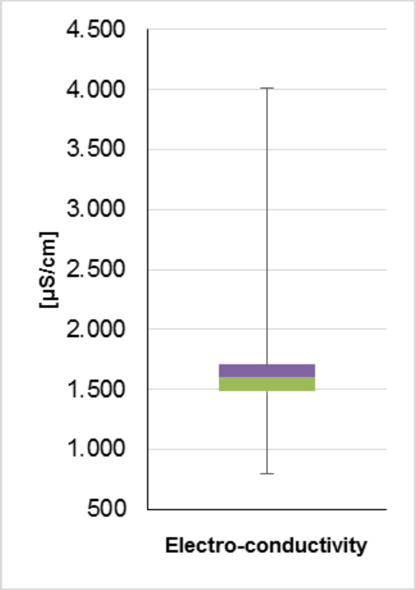


Fig. 4.5: Measured electro-conductivity, PS1: 17.06 - 06.12.2014 (101 samples).

The measured pH values (Fig. 4.6) are relatively consistent, with interquartile range of 7.7 - 7.9 (median 8.0). The maximum pH was 9.20 and minimum 7.06. Serbian households mainly rely on handwashing dishes, with dishwasher still not a common standard; this practice increases detergents consumption, which can increase pH.

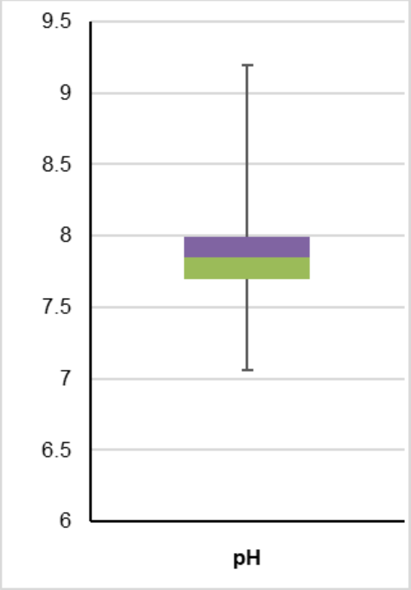


Fig. 4.6: Measured pH, PS1: 17.06 - 06.12.2014 (101 samples).

4.1.1.3 Pollutant Concentrations

Fig. 4.7 shows the concentration range of measured Total Solids (TS), total fixed solids (TFS) and total volatile solids (TVS). The range of the measured TS varies widely from 650 to 4,300 mg/l) but is steady in the interquartile range: 1,200 to 1,600 mg/l (median 1,396 mg/l, average 1,450 mg/l). TFS are in the range 320 to 2,700 mg/l (median 900 mg/l, average 933 mg/l), while TVS ranges from 180 to 1,600 mg/l (median 496 mg/l, average 520 mg/l). Considering the literature values (Tab. 2.1) measured TS correlate to "strong" polluted wastewater.

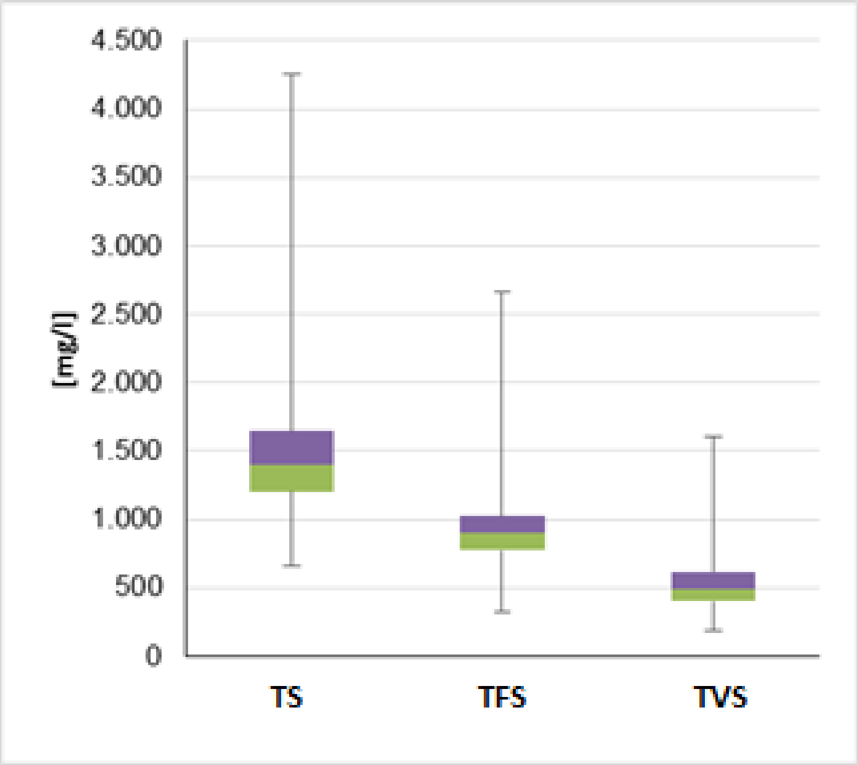


Fig. 4.7: *Measured total solids (TS), total fixed solids (TFS) and total volatile solids (TVS), PS1: 17.06 - 06.12.2014 (101 samples).*

Total Suspended Solids (TSS) was measured for 68 samples, shown in Fig. 4.8. The TSS ranges from 130 to 390 mg/l, with more consistent 50% range of 220 to 320 mg/l. Average TSS is 265 mg/l; these results indicate "weak" wastewater.

High TS combined with relatively low TSS indicates the presence of dissolved solids (inorganic salts), which correlates with the high electro-conductivity. Dissolved solids may be entering from untreated wastewater from an organic industry such as meat or dairy processing. The high TS indicates a “strong polluted” wastewater. During wet-weather days, TS increased while TSS remained low, so we derive that some quantity of solids like fine sand or soil are being washed and transported by the sewer. This was confirmed by the fact that the inorganic part of the TS was shown to contribute 66% of TS. Such infiltration is to be expected considering the number of breaks in the sewer system, combined with high run-off from agricultural lands.

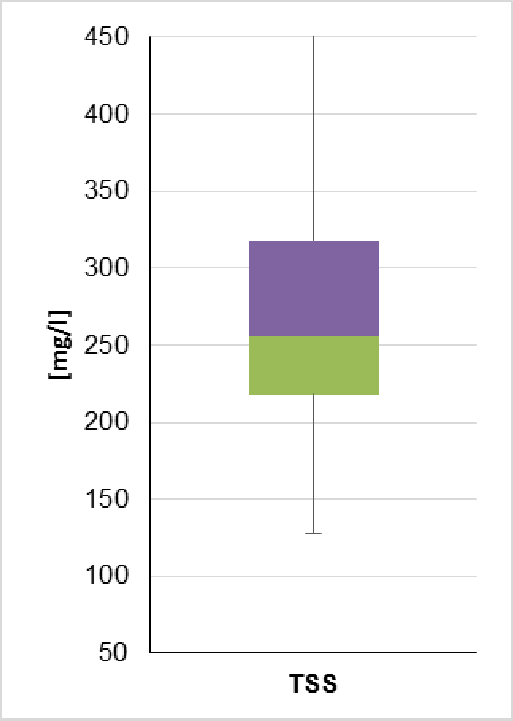


Fig. 4.8: Measured total suspended solids (TSS), PS1: 17.06 - 07.12.2014 (68 samples).

Organic pollution (Fig. 4.9) was consistent in concertation: COD 140 to 1,380 mg/l (median 407, average 432 mg/L); and BOD 44 to 720 mg/l (median 192, average 210 mg/L). Due to the presence of food companies, high COD is to be expected. However, measured COD indicates “weak” polluted wastewater; this may be explained by infiltration during rain events (Chapter 4.1.1.1) and industrial wastewater pre-treatment that many of surveyed companies confirmed.

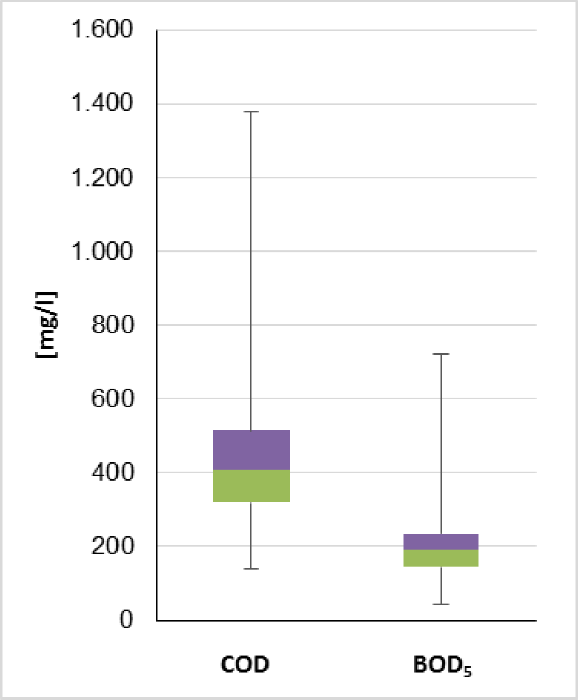


Fig. 4.9: *Measured chemical oxygen demand (COD) and biological oxygen demand (BOD) concentrations, PS1: 17.06 - 07.12.2014 (101 samples).*

Nutrient pollution is expressed in nitrogen (Fig. 4.10) and phosphorus (Fig. 4.11). concentrations. The range of total nitrogen (N_{tot}) was wide (15 to 67 mg/l) and relatively unsteady within the interquartile range of 32 to 49 mg/l. The average nitrogen concentration was 40 mg/l, indicating a ''weak'' to ''medium'' polluted wastewater. Similar dynamics apply for the ammonium-nitrogen (NH_4-N) (Fig. 4.10a) with a minimum measured concentration of 3 mg/l, a maximum of 58 mg/l, interquartile rage of 20 to 37 mg/l, and a median of 29 mg/l). Nitrate-nitrogen (NO_3-N) concentrations were more consistent, with interquartile range of 0.33 to 0.54 mg/l, minimum < 0.02 mg/l, maximum 2.0 mg/l (Fig. 4.10b), and average 0.56 mg/l. Certain extreme values of total nitrogen are likely attributed to wastewater from dairy and meat processing (including blood). Ammonium is largely attributed to septic tank waste and animal manure (Breisha, Z.G, 2010; EPA, 2004), so the observed peaks of ammonium-nitrogen (58 mg/l) were likely caused by illegal discharges of septic tanks and animal manure in this case as well.

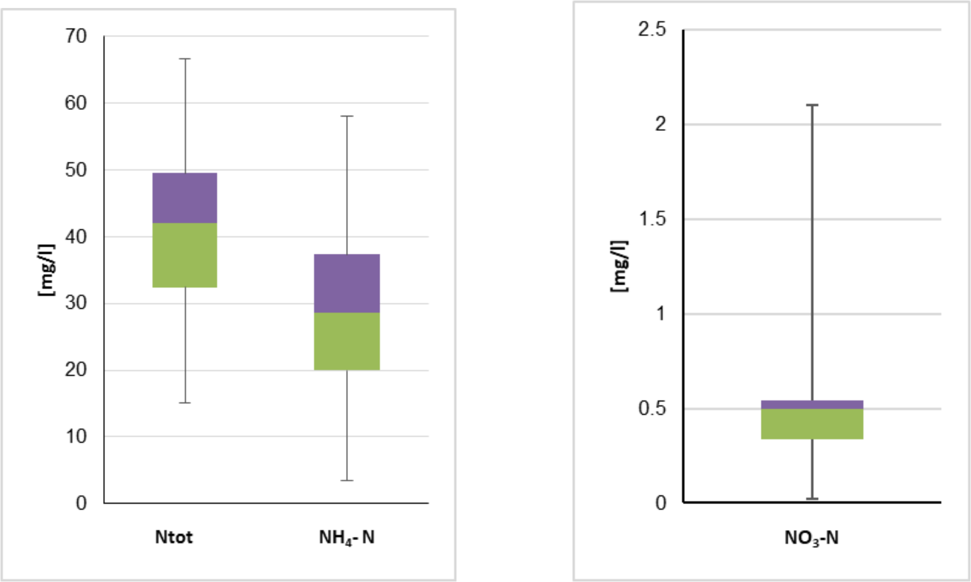


Fig. 4.10: Measured total nitrogen (N_{tot}), ammonium - nitrogen (NH_4-N) (a) and nitrate – nitrogen (NO_3-N) (b) concentrations, PS1: 17.06 - 07.12.2014 (101 samples).

As seen in Fig. 4.11, measured orthophosphate-phosphorus (PO_4-P) ranges from 0.16 to 3.4 mg/l, median 1.0 mg/l, and relatively constant 50% range of 0.9 to 1.6 mg/l. Total phosphorus (P_{tot}) is in the higher range of 1.2 to 9.0 mg/l, with median 3.0 mg/l, and 50% range of 2.63 to 4.0 mg/l. Average orthophosphate-phosphorus was 1.45 mg/l and phosphorus 3.61 mg/l. These values are significantly lower than literature values characterizing “weak’’ wastewater.

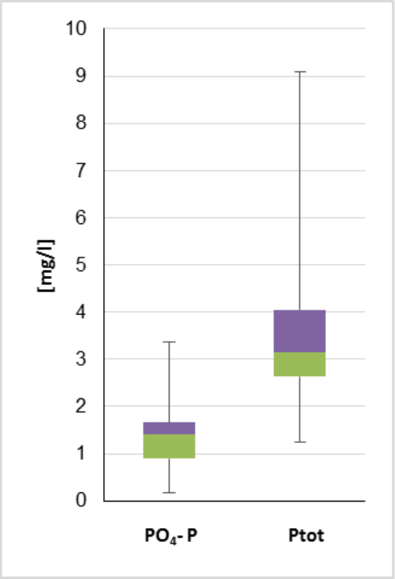


Fig. 4.11: Measured orthophosphate-phosphorus (PO_4-P) and total phosphorus (P_{tot}) concentrations, PS1: 17.06 - 07.12.2014 (101 samples).

The average BOD/COD ratio is 2.0, which indicates plausibility, and good wastewater degradability. As seen in Fig. 4.12 left the COD/BOD ratios reach up to 2.4 in 75% of the cases, indicating "typical'' municipal wastewater quality and good degradability per literature (Henze, 2008). C/N ratio is up to 13.0 in 75% of cases, indicating favourable conditions for denitrification. While nitrogen results are plausible (COD/N_{tot}=12), measured total phosphorus concentrations were discarded as implausible, given that COD/P_{tot}=189, far beyond what are considered typical, COD/P_{tot} = 20-60 (Heneze 2008).

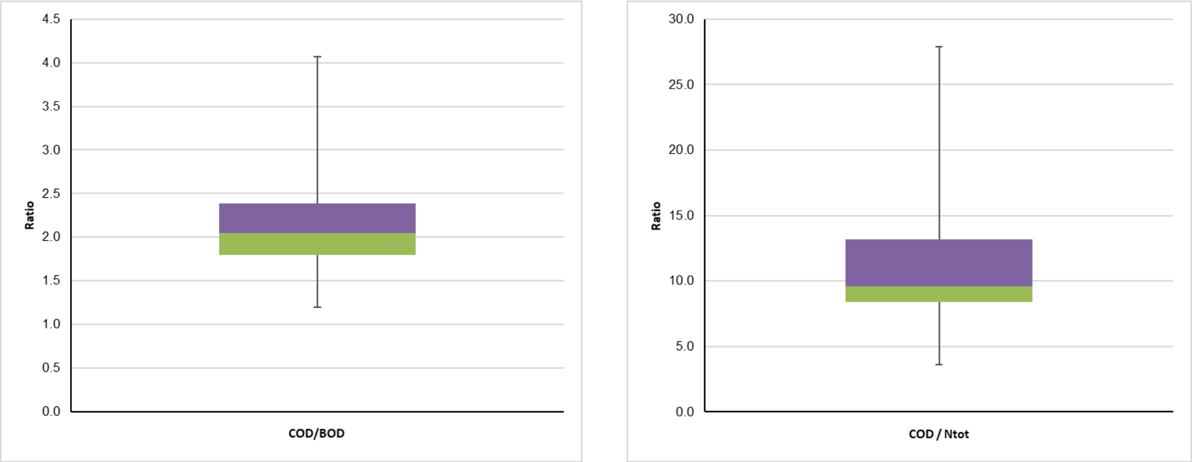


Fig. 4.12: COD/BOD ratio and COD/N_{tot} ratio, PS1: 17.06 - 07.12.2014.

An overall summary of the measured pollutants concentrations during the measurement campaign (101 samples) and the derived pollutant loads (based on Equation 3.3) are summarized in Tab. 4.3.

Based on the results of measurement campaign compared with literature values (Tab. 2.1), wastewater in the CSR can be characterised as "weak" to "medium" polluted. Given that the water consumption rate in the CSR is moderate (142 l/(cap*d), Tab. 4.1), the low pollutant values indicate that wastewater is diluted by infiltration (Q_{Inf}=96%Q_{WW}). The high organic pollution concentrations (COD 1,380 mg/l; BOD_5 720 mg/l); peak electro-conductivity; and relatively low TSS concentrations indicate occasional illegal industrial wastewater discharges (most likely food processing). However, average contractions for TSS, COD and BOD_5 still indicated "weak" wastewater pollution. There are two potential reasons for this: first, industrial wastewater is pre-treated as required; or second, it is possible TSS, COD and BOD_5 are lower due to the sedimentation losses caused by the upstream pumping station. The auto-sampler was located directly after the wastewater pump, so even though the wastewater is well mixed before pumping, some larger particles such as sand or soil, may partly settle, reflecting in a lower TS than its actual value. The plausibility of this was confirmed by measuring TS for the two-hour composite sample, which was sampled at ten-minute intervals and mixed, obtained on July 21, 2014. In this case measured TS value was 1,896 mg/l, which is higher than the average of the entire campaign, 1,450 mg/l. A similar pattern is observed in the TSS results, implying that measured TSS concentrations were most likely lower due to sedimentation caused at the pumping station.

Tab. 4.3: Overview of the measured pollutant concentrations and derived loads (101 samples).

	Concentration Range					Load Range		
	Dry Weather		Wet Weather					
	Min	Max	Min	Max	Average	Min	Max	Average
	(mg/l)		(mg/l)		(mg/l)	(kg/d)		(kg/d)
TSS	197	385	150	392	265	1,419	8,387	3,728
TS	958	2,094	654	4,260	1,453	6,658	63,896	21,939
TFS	326	1,348	326	2,660	933	4,765	39,897	13,992
TVS	194	919	186	1,600	520	1,894	23,998	7,992
COD	192	1,380	140	820	432	1,284	13,575	6,043
BOD_5	95	720	44	720	210	635	7,059	2,807
N_{tot}	16	67	15	65	40	106	1,489	562
NH_4-N	12	47	3	50	29	37	1,024	383
NO_3-N	0.02	2.06	0.03	2.00	0.56	0.46	32	8
PO_4-P	0.56	3.36	0.16	3.00	1.45	3.10	63	22
P_{tot}	1.24	9.1	1.8	8.0	3.6	14	157	56

4.1.1.4 Diurnal Pollutant Concentration Variation

Flow rates and pollutant concentration in wastewater are prone to vary due to factors including changes in lifestyles and standards of living, industrial production patterns and seasonal weather variations. To check the behaviour of the sewer system in the CSR, diurnal pollutant concentrations and flow variations were examined. Twelve two-hour samples were collected from November 18-19 (6:00 a.m. – 6:00 a.m.); roughly 2 mm rain fell on November 18 from 9:00 a.m. until 2:00 pm. The auto-sampler took a sample every four minutes. Fig. 4.13 summarises the recorded flows and BOD and TSS during the 24h period. As seen, minimum flow occurs late night (after midnight) and early morning, as water consumption is lowest during those times; then, the flow consists of smaller quantities of sanitary wastewater, plus infiltration.

The first wastewater flow peak was recorded in the morning from 7:15 – 8:15 a.m. (Fig. 4.13). While this might seem late, there is a 1-2-hour delay for wastewater generated to reach PS-1, which is located at the very end of the sewer catchment. Given that the rain started at 9:00 a.m., a second peak is observed around 11 a.m. (Fig. 4.13). Although the concentration of the BOD_5 and TSS comply with each other, it is also clear that significantly higher BOD and TSS concentrations were measured at the beginning of the rain event (9:30- 10:00 a.m.). This could have been caused by “first flush effects” originating from settled material in the sewer system, or discharge from polluted surface water. As expected, after several hours dilution occurs, and BOD and TSS concentrations decrease. The next two peak flows occur in the afternoon, the first at 4:15 -5:45 p.m., coinciding following mid-day meals; and next at around 7 p.m., following the end of the workday. BOD also then reaches a peak, before declining overnight.

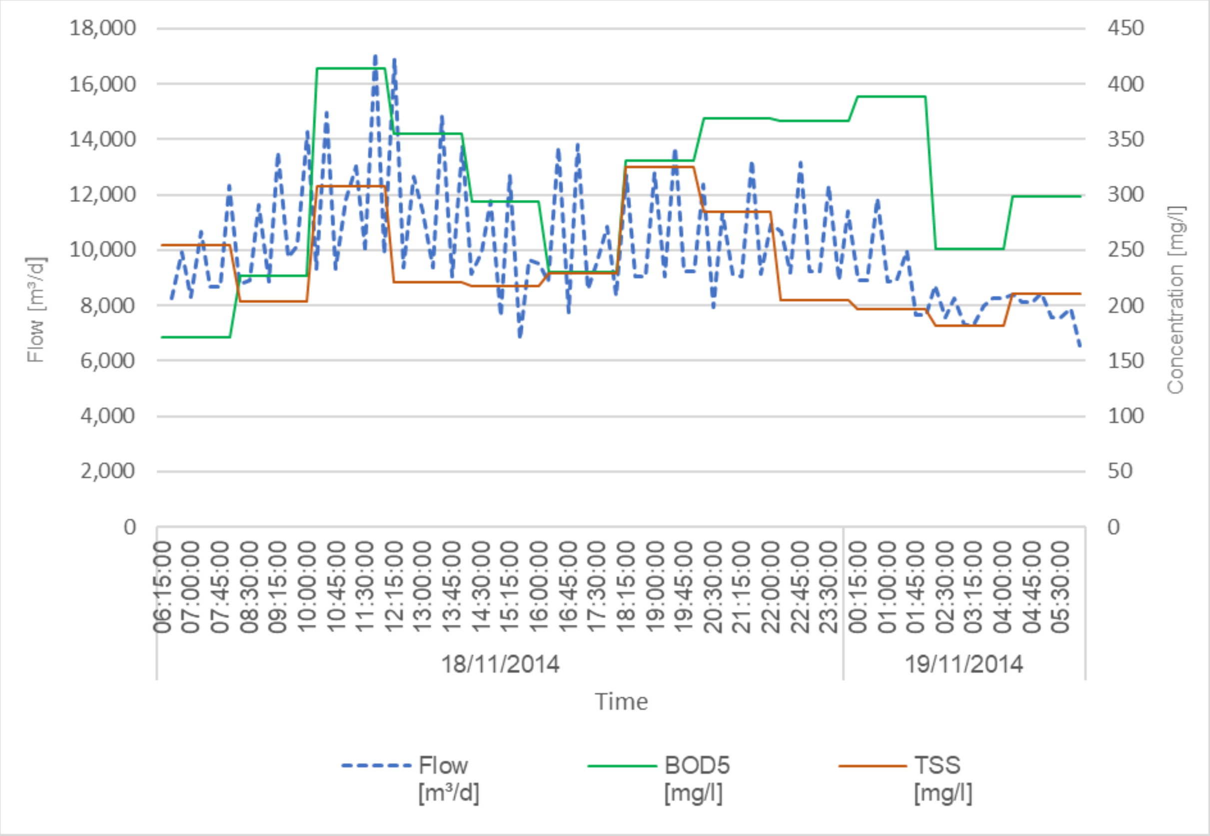


Fig. 4.13: Diurnal variations of flow and loadings of domestic wastewater (Wed.,18.11.2014, 6:00 a.m. – Thurs.,19.11.2014, 6:00 a.m.)

4.1.1.5 Pollutant Derived Loads

Regarding the Industrial Waste Survey (Appendix 1) most of the companies do not work weekends. To check pollution originating solely from the population, and thus propose inhabitant-specific pollutant loads, weekend days were examined (excluding July and August due to intensified food processing). Tab. 4.4 summarises recorded pollutant concentrations and derived loads on weekends based on Equation 3.4 and 22 weekend measurements.

Tab. 4.4: Overview of measured pollutant concentrations and derived loads during weekend (22 samples).

	Concentration Range Dry Weather			Load Range		
	Min	Max	Average Concentration	Min.	Max	Average Load
	(mg/l)		(mg/l)	(kg/d)		(kg/d)
TSS	193	331	249	1,419	8,387	2,617
TS	654	1,826	1,339	6,658	46,875	16,486
TFS	468	1,178	888	4,765	19,208	9,500
TVS	186	818	451	1,894	11,387	4,807
COD	173	820	380	1,284	7,323	3,861
BOD_5	54	484	194	635	4,412	1,957
N_{tot}	15	64	35	106	751	375
NH_4-N	6	40	26	14	142	37
NO_3-N	0.11	1.46	0.49	1.41	14	5.12
PO_4-P	0.70	2.4	1.4	5	40	16

Based on numerous wastewater quality and flow analyses, many countries have developed national WWTP design guidelines (e.g. German Standard ATV-DVWK-A-131E “Dimensioning of Single-Stage Activated Sludge Plants” (ATV, 2000), design recommendations given in the book “Wastewater Engineering: Treatment and Reuse” (Tchobanoglous, 2003)). These guidelines provide “inhabitant-specific loads”, which are loads on per capita and daily basis. Inhabitant-specific loads vary between countries due to different catchment area properties, socio-economic and lifestyle factors, water usage patterns, household types, and industrial wastewater. In the absence of a national WWTP design standard for Serbia, this research calculated pollutant loads from data gathered during the measurement campaign, in accordance with Equation 3.5, and derived 85% and 60% fractile loads from weekend days. Tab. 4.5 summarizes the results of the inhabitant-specific loads for main pollutants and compares them to literature values (ATV, 2000, Heneze, 2008 and Tchobanoglous et al., 2003). Phosphorus values were discarded as not plausible.

Tab. 4.5: Derived inhabitant-specific pollutant loads compared to literature values.

	85% Fractile		60% Fractile		Reference Values		
	Daily Load	Inhabitant Specific Load	Daily Load	Inhabitant Specific Load	ATV, 2000	Henze, 2008	Tchobanoglous et al., 2003
	(kg/d)	(g/(cap*d))	(kg/d)	(g/(cap*d))	(g/(cap*d))		
TSS	3,700	90	2,825	67	70		90
COD	6,400	155	4,400	105	120	25-200	190
BOD_5	3,500	85	2,400	57	60	15-80	80
N_{tot}	580	14	500	12	11	2-15	13

As seen in Tab. 4.5, calculated inhabitant-specific loads deviate from typical literature WWTP design values. The German technical standard ATV-DVWK-A-131 (ATV, 2000) precisely recommends using 85% fractile value to determine inhabitant-specific loads for design purposes. In the case of the other two norms (Tchobanoglous et al., 2003 and Henze, 2008) it is not clearly defined. If the 85% fractile is used, the derived inhabitant-specific loads are higher than those proposed by the technical standard ATV-DVWK-A-131 (Tab. 4.5), while closer to the American design guidelines proposed by the Tchobanoglous et al., 2003. Inhabitant-specific loads derived from the 60% fractile come close to the design values proposed by the technical standard ATV-DVWK-A-131. This is presently only a preliminary estimation and should be used with caution. First, only 22 measurements were recorded. Second, inhabitant pollutant loads were derived using the population of the sewer catchment area (42,000 inhabitants) delivered by the PUC. In actuality, there may be a higher connection rate than reported by the PUC, in which case results based on 85% fractile would lie closer to technical standard ATV-DVWK-A-131. Furthermore, the derived loads on days with reduced industrial activity might also be positively influenced by some of the “illegal’’ industrial wastewater discharges (e.g., meat and dairy) which are not connected to the sewer, but occasionally illegally discharge wastewater into the sewer over the weekend. On the other hand, as previously mentioned, the pumping station may also have caused the sedimentation and the lower TSS, BOD_5 and COD, while the dissolved substances like ammonium are not affected by sedimentation.

As the monitoring campaign demonstrated, the importance of properly understanding the sewer catchment area is of utmost importance. In this case, the main challenge was to understand the influence of industrial wastewater pollution on municipal wastewater quality. Despite considerable effort dedicated to data collecting on industrial wastewater quality in the CSR, the list of industries listed in Appendix 1 is incomplete. Many small, family-own businesses were not recorded because they were not present in the official municipal registers, while others declined to be surveyed. For the identified companies, only flows were collected, as none of the companies provided water quality data. It is therefore difficult to fully understand the influence of industrial wastewater discharge on the overall wastewater quality.

4.1.1.6 Wastewater input data for the Decision Support Tool

The status quo analysis revealed that only ca. 37% of the population (42,000 inhabitants) and ca. 50% of existing industrial units are connected to the sewer system. Based on the official development plans of Municipalities Stara Pazova and Indjija, the entire population (114,000 inhabitants, Tab. 3.1) and all industrial units should be connected to wastewater treatment.

Based on the results of the measurement campaign, 85% fractile value of derived BOD_5 loads from 101 samples amounts to 5,100 kg/day (mean value of 2,870 kg/day; Tab. 4.4), originating in parts from the population and from industry. For 22 weekend measurements, when industrial activity is low, the 85% fractile value of BOD load amounts to 3,500 kg/day (mean value 1,957, Tab. 4.4). Thus, it can be derived that BOD originating from industry equates to 1,600 kg/day. By applying a derived inhabitant-specific BOD load of 85 g/(Cap*day) (Tab. 4.5), the treatment capacity requirement equals 19,000 PE (Tab. 4.6). For the future, industrial connection rates are assumed to reach 100%, while industrial activities (and waste output) are expected to increase by 25%; thus, the future treatment capacity as a result of industrial activities is 47,500 PE. For domestic wastewater, the current population is assumed to remain constant at 114,000 PE.

As the CSR consists of both urban and rural settlements, in addition to a centralized WWTP, decentralized units could serve up to twelve settlements: two peri-urban with 6,000 inhabitants served by an SBR process, plus ten rural settlements of 16,000 inhabitants by constructed wetlands (CW). The balance of 92,000 inhabitants would be served by a central WWTP with a capacity of 139,000 P.E.

Tab. 4.6: Wastewater flow and treatment capacity – status quo (2014) and future estimation.

	$Q_{Dom,aM}$	$Q_{Ind,aM}$	PE population	PE industry	Total PE
	(m^3/d)	(m^3/d)			
Status Quo (2014)	5,879	1,788	42,000	19,000	61,000
Future estimate	16,302	4,471	114,000	47,500	161,000

4.1.2 Waste Sector

In Stara Pazova, waste is collected for 73% of households, amounting to 26,000 t/a or 400 kg/(cap*a). Per capita waste generation for Stara Pazova is thus higher than the Serbian average of 268 kg/(cap*a), and closer to the EU-27 rate of 488 kg/(cap*a) (Fig. 2.10). Bio-waste amounts for 60% of municipal waste generation, higher than reported literature values of ca. 50% (Vujice et al., 2015). Based on the Bio-Waste Survey (Appendix 2) food waste accounts for 86% of total volume, market grass 12,5%, and green cut 1,5% (Tab. 4.7). Industries, notably beverage, food, dairy and meat, also generate organic waste. The biodegradable fraction reaches its two extreme values in the second half of spring and in early autumn. Presently, collected municipal waste is disposed of at the central, non-sanitary landfill “Rupov Salas” and at several unregulated dumping sites

Tab. 4.7: Available bio-waste flows in Stara Pazova municipality (2012)

	Quantity
	(t/a)
Kitchen waste	25,050
Grass	3,737
Green cut	299
	29,086

4.1.3 Agriculture Sector

The municipality of Stara Pazova has 30,000 ha of agricultural land, of which 75% is used for crop production. Based on our Agriculture Survey (Appendix 3), the total annual crop yield based on our sample (Fig. 3.5) and period 2003-2012 is represented in Fig. 4.14. Dry years from 2003-2012 significantly reduced corn yield, dropping from 8-9 t/ha to only 3 t/ha. As a result, and as seen in Fig. 4.14, the highest yield was achieved in 2010, whereas two years later, the yield drops by ca. 60%.

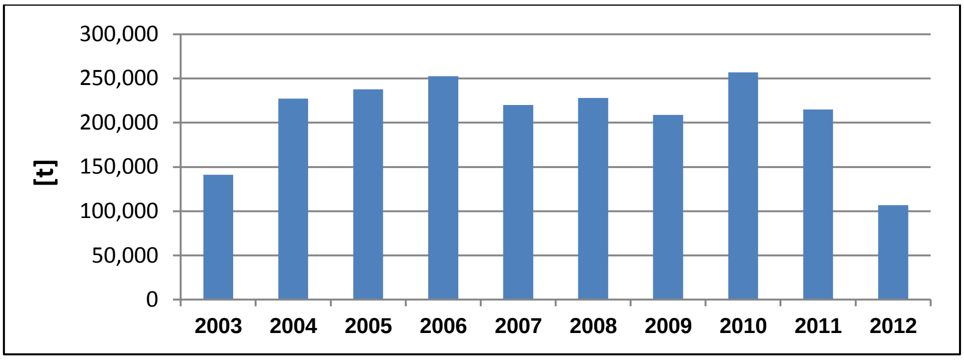


Fig. 4.14: *Total annual crop yield for the period 2003-2012 based on Agriculture Survey.*

Based on the survey sample the most cultivated crop is corn (15,000 ha/a; 46% of the total crops cultivated), followed by wheat and sugar beet (both roughly 5,000 ha/a; 18% of the total crops cultivated) (Fig. 4.15).

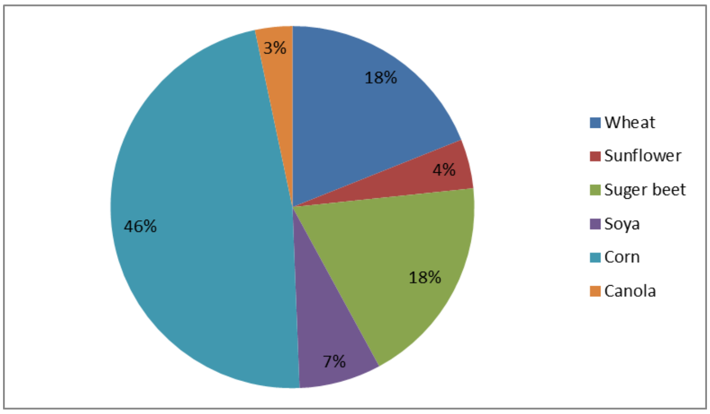


Fig. 4.15: *Crop structure based on survey.*

If we consider annual yield in tonnage by crop cultivation (Fig. 4.16) in the previous ten years, sugar beet had the highest yield (140.000 t/a or 58 t/ha), followed by corn (42.000 t/a or 8 t/ha), and then wheat (5.700 t/a or 6 t/ha).

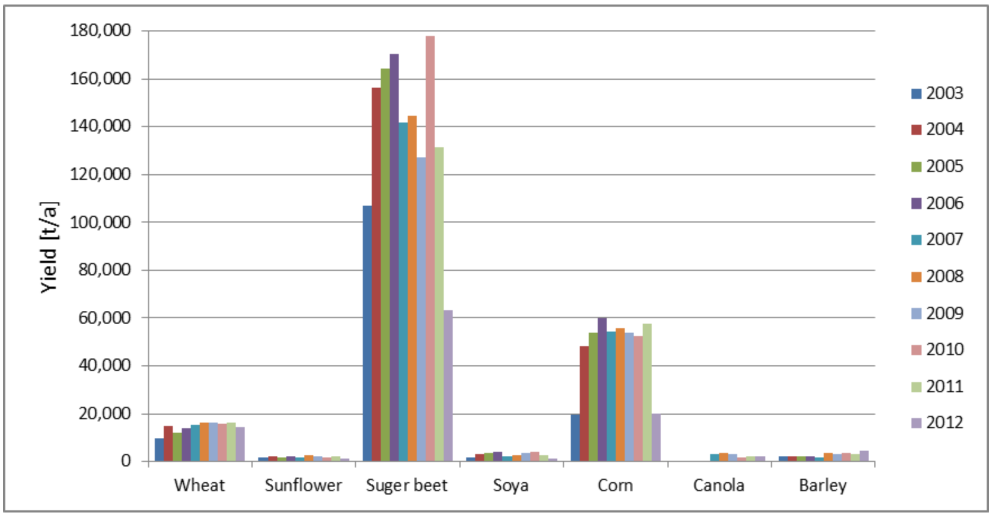


Fig. 4.16: Annual crop yield for the period 2003-2012 based on Agriculture Survey.

Tab. 4.8 summaries data on average annual crop biomass yields from 2003-2012, with 95% confidence interval and based on the results of our Agriculture Survey. Furthermore, the Table presents approximate percentage of silage per crop reported by farmers not be utilised (and thus considered as agro-waste) and the the estimated agro-waste biomass. Wheat straws is commonly used for animal stables, and thus is the least available waste flow. Alternatively, farmers reported that sugar beet waste is not further utilized. As such, it presents an issue for farmers and is usually burned on fields, offing no further utilization value.

Tab. 4.8: Overview of available biomass flows per crop based on a survey during period 2003-2012.

	Biomass annual yield	95% Confidence Interval (minimum)	Percentage silage not used by the farmer	Available biomass (based on 95% confidence interval)
	(t/a)	(t/a)	(%)	(t/a)
Corn	52,720	40,918	90	36,826
Wheat	35,885	32,063	40	12,825
Barley	3,204	1,963	90	2,181
Sugar beet	138,478	114,039	100	114,039
Sunflower	2,034	1,727	90	1,554
Canola	1,545	523	90	471
TOTAL	232,321	190,710		

Besides crops, livestock breading is also common in Stara Pazova. However, waste flow is only available to a limited extent since farmers typically reuse manure as fertiliser applied to their fields. Tab. 4.9 summarizes estimated available biomass from livestock based on the Agriculture Survey, which estimates ca. 37.000 animals are kept by the local farmers generating ca. 2,000 t/a of unutilized waste. Pig manure contributes over 80% of the total generated manure. Unutilized manure typically ends in the central landfill or is discharged into the Danube River.

Tab. 4.9: Overview of available biomass flows per animal type based on Agriculture Survey

		Number of animals	Available substrate quantities	Agro-waste (manure)
			[%]	[t/a]
Pigs	Piglets	18,785	12	1,133
	Fattened	14,700	1	682
	Sows	2,399	1	27
Cattle	Calves	121	18	7
	Heifers	140	4	20
	Pregnant heifers	153	3	147
	Breeding cows	130	13	29
	Bulls	370	0	0
Horses		2	0	0
Poultry		50	100	0.47
TOTAL		37,178		2,045

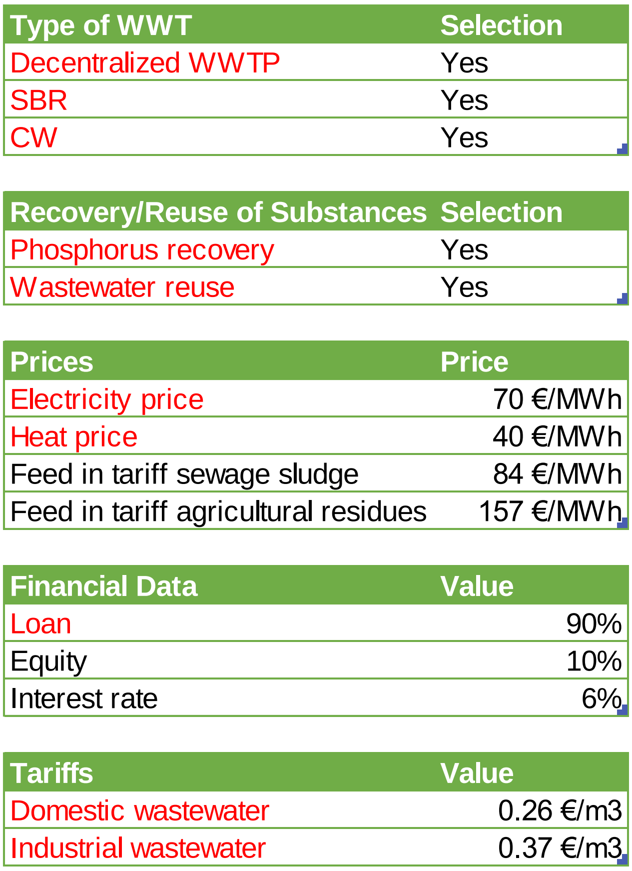
4.2 Decision Support Tool

As discussed in Chapter 2.4 integrated wastewater-organic material flows concepts are not yet widely in practice. Typically, the Circular Economy approach has been applied to single sectors, resulting in concepts such as “zero waste”, “zero emission”, and “zero wastewater discharge”. All these have in common resource circularity and seek to maximise value within the bounds of a single sector. This research goes a step further and proposes integrated resource management across different sectors. The developed DST (Appendix 6, example of the Scenario “d-4”) calculates and quantifies potential synergies across all of the potential sectors and optimizes value-adding and process parameters. Based on user input, the DST analyses and quantifies potential energy generation, phosphorus recovery and wastewater re-use for one of 16 possible treatment scenarios. Furthermore, by comparing two variants of a given user-based scenario, it is possible for the user to compare conventional, centralised treatment (Variant 1 in this research) with a modular, decentralized approach for remote rural settlements utilizing dual digesters (Variant 2 in this research). Lastly, the DST provides economic analysis and compares the two variants of any given user-based scenario.

4.2.1 Testing the Decision Support Tool

Although the DST is intended to be universally applicable for various integrated scenarios, it was applied and tested using the data from that Serbia Case Study Region (CSR). Given that there are 16 possible scenarios which DST may calculate (Tab. 3.5.). For the purposes of our research case study, Scenario “d-4” was selected, as it is holistically orientated and integrates decentralized and centralized wastewater treatment, with the possibilities for phosphorus recovery and wastewater re-use.

As explained in Chapter 3.3.3.2.1, in the first worksheet (Excel) of the DST “User Input Selection” (Fig. 4.17), the user completes mandatory fields (marked red). For the case study, “Type of WWT” is decentralized wastewater treatment; “Recovery/Reuse of substances” includes phosphorus recovery and wastewater reuse, consisting in turn of constructed wetlands (CW) and sequence batch reactor (SBR) (Fig. 4.17). Market prices are inputted, for the case study, electricity 70 €/MWh; district heating 40 €/MWh (2014). In the “Financial Data” section, a loan financing 90% of capital cost was assumed to be the maximum that Serbian municipalities can receive from development banks (e.g., KfW bank, EBRD) for environmental infrastructure. In “Tariffs” domestic wastewater was costed at 0.26 €/m^3 and industrial wastewater at 0.37 €/m^3, based on current data.



Type of WWT	Selection
Decentralized WWTP	Yes
SBR	Yes
CW	Yes

Recovery/Reuse of Substances	Selection
Phosphorus recovery	Yes
Wastewater reuse	Yes

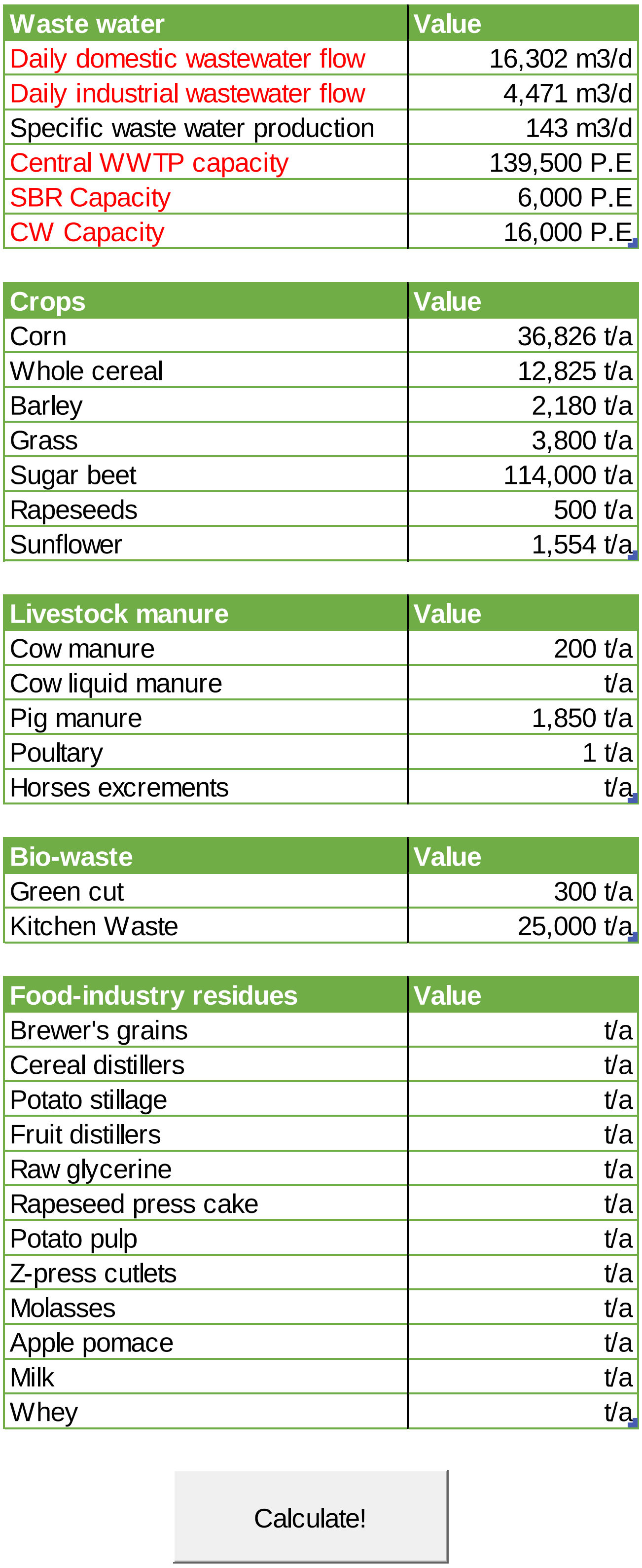
Prices	Price
Electricity price	70 €/MWh
Heat price	40 €/MWh
Feed in tariff sewage sludge	84 €/MWh
Feed in tariff agricultural residues	157 €/MWh

Financial Data	Value
Loan	90%
Equity	10%
Interest rate	6%

Tariffs	Value
Domestic wastewater	0.26 €/m3
Industrial wastewater	0.37 €/m3

Fig. 4.17: DST testing – Input data in the “User input selection” tab for the CSR.

The next tab, “User input flow” tab (Fig. 4.18), includes the available waste flows (input data are shown). “Wastewater” includes both domestic and industrial flows are based on the results presented in Tab. 4.6. Crops values are based on the data presented in Tab. 4.8; livestock data is taken from Tab. 4.9; and biomass flows from Tab. 4.7.



Waste water	Value
Daily domestic wastewater flow	16,302 m3/d
Daily industrial wastewater flow	4,471 m3/d
Specific waste water production	143 m3/d
Central WWTP capacity	139,500 P.E
SBR Capacity	6,000 P.E
CW Capacity	16,000 P.E

Crops	Value
Corn	36,826 t/a
Whole cereal	12,825 t/a
Barley	2,180 t/a
Grass	3,800 t/a
Sugar beet	114,000 t/a
Rapeseeds	500 t/a
Sunflower	1,554 t/a

Livestock manure	Value
Cow manure	200 t/a
Cow liquid manure	t/a
Pig manure	1,850 t/a
Poultary	1 t/a
Horses excrements	t/a

Bio-waste	Value
Green cut	300 t/a
Kitchen Waste	25,000 t/a

Food-industry residues	Value
Brewer's grains	t/a
Cereal distillers	t/a
Potato stillage	t/a
Fruit distillers	t/a
Raw glycerine	t/a
Rapeseed press cake	t/a
Potato pulp	t/a
Z-press cutlets	t/a
Molasses	t/a
Apple pomace	t/a
Milk	t/a
Whey	t/a

Fig. 4.18: DST testing – Input data in the “User input flow” tab for the CSR.

Based on the preferences selected in the “User Input Selection” (Fig. 4.17.) and the input data inserted in the “User Input Flow” (Fig. 4.18) and by pressing “Calculate” the tool calculates and graphically present the results of the two compared variants.

The DST provides a graphic visualization of the integrated concept. Fig. 4.19 shows the results of the tested CSR (Scenario “d-4”) for Variant 1 and Fig. 4.20 shows Variant 2. On the input side, the user can see quantified potentials of waste flows. Then, based on a mass balance, the graphic shows all related intermediate and output flows and compositions of sewage sludge, organic flows from agriculture and waste management, recovered phosphorus, digestate for fertilizer (Variant 2), slurry for further treatment options, and potential thermal and electrical energy.

Variant 2 (Fig. 4.20) helps to understand the impact of applying a “modular” approach with decentralized wastewater treatment and the application of two digesters. In addition, Variant 2 helps to understand the potential for combining infrastructure to accommodate integrated management, and realizable benefits of producing high quality substrates. Variant 2’s two digesters separate clean biomass flows from agriculture from potentially contaminated flows from wastewater and waste management sectors. This is important in agriculture regions, as these streams represent “clean” material that can be directly re-used after digestion.

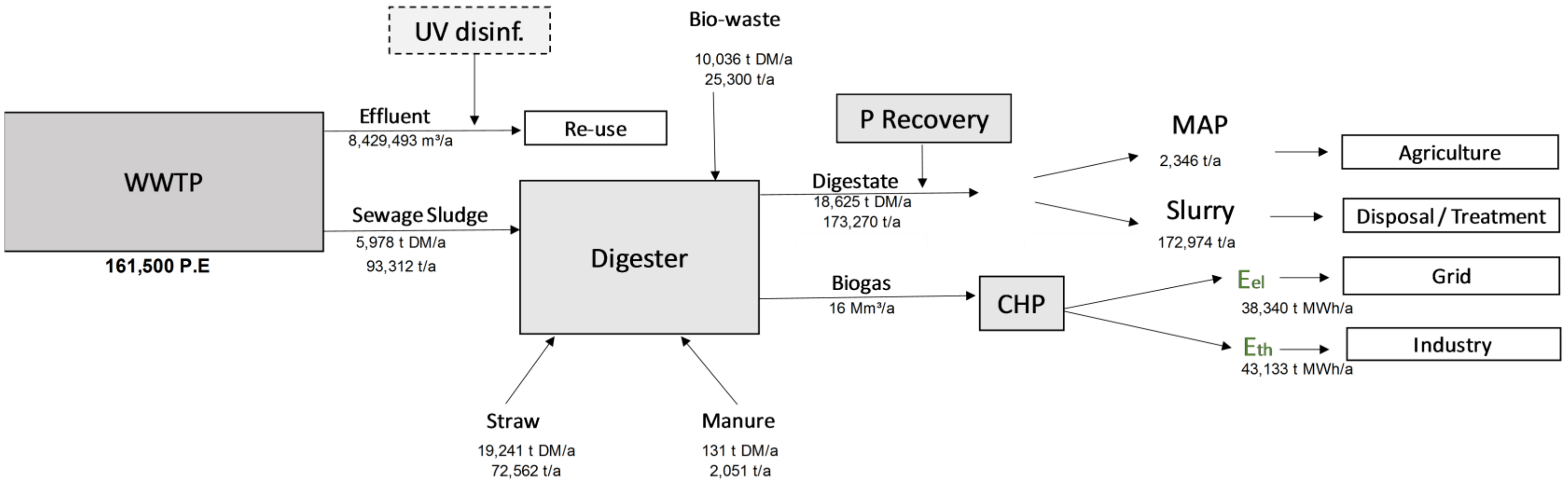


Fig. 4.19: Results of the Scenario d-4, Variant 1 (centralized).

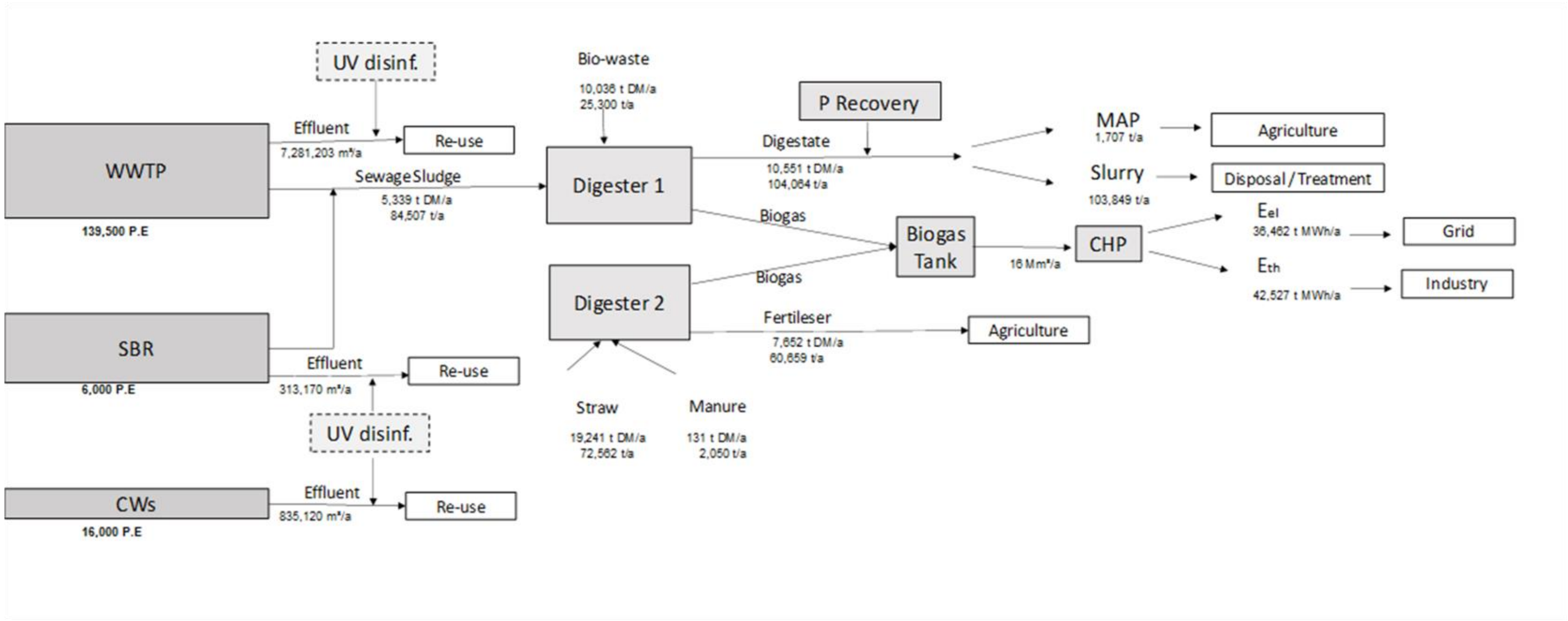


Fig. 4.20: Results of the Scenario d-4, Variant 2 (decentralized).

Based on the input data for the CSR, the amount of thickened sewage sludge available for the anaerobic digestion process is ca. 6,000 t DM/a for Variant 1 (Fig. 4.19) and ca. 5,340 t DM/a for Variant 2 (Fig.4.20). Biomass available for co-digestion includes 17,553 t DM/a (67,328 t/a) of straw; 131 t DM/a (2,050 t/a) of livestock manure; and 10,036 t DM/a (25,300 t/a) of municipal bio-waste. This mixed substrate would produce ca. 15 Mil.m^3 of biogas annually. Summaries of energy demand and material flows of the two variants is presented in Tab. 4.10. After subtracting energy demand for the treatment process and digesters, sludge and digestate dewatering, and disinfection there is a surplus of electrical energy (net electricity) of 77% of the gross produced electrical energy (29,225 MWh$_{el}$/a for Variant 1; 28,000 MWh$_{el}$/a for Variant 2). The estimated gross thermal energy production is ca. 43,000 MWh$_{th}$/a (Tab. 4.10), of which ca. 30% is required to heat the digester and to dry digestate (net heat production 30,739 MWh$_{th}$/a for Variant 1 and 30,294 MWh$_{th}$/a for Variant 2).

Tab. 4.10: Energy demand and production potential of Scenario d-4 and two variants for the tested CSR input data

	Variant 1	Variant 2
Gas Production Digester 1	15,963,625 m^3/a	4,594.338 m^3/a
Gas Production Digester 2	-	11.162.240 m^3/a
CHP capacity	9MW	9MW
Gross electricity production	**38,341 MWh/a**	**36,462 MWh/a**
Electricity demand Digester 1	2,914 MWh/a	837 MWh/a
Electricity demand Digester 2	-	1,935 MWh/a
WWTP -wastewater treatment, sludge and digestate dewatering	5,949 MWh/a	5,464 MWh/a
WWTP Energy demand disinfection	253 MWh/a	218 MWh/a
SBR Energy demand disinfection	-	9 MWh/a
CW Energy demand disinfection	-	8 MWh/a
Net Electricity	**29,225 MWh/a**	**28,000 MWh/a**
Gross heat production	**43,133 MWh/a**	**42,527 MWh/a**
Heat demand Digester 1	12,077 MWh/a	3,467 MWh/a
Heat demand Digester 2	-	8.440 MWh/a
Heat demand for WWTP- digestate drying	317 MWh/a	331 MWh/a
Net Heat	**30,739 MWh/a**	**30,294 MWh/a**

For Variant 1 (Fig. 4.20), the expected digestate outputs equate to 18,625 t DM/a (173,270 t/a); processing this substrate through a Stuttgart process will result in recovery of ca. 2.400 t MAP (304 t P/a) annually. In accordance with EU legislation, the remaining slurry (172,974 t/a) would require additional treatment, as digestate from co-digestion may contain cause environmental and/or health risks; thus, this remaining slurry would need further disposal. Depending on individual countries' regulations, certain solutions such as soil conditioning or further composting may be possible; in stricter regulatory environments, co-incineration may be an option. In non-EU countries, landfilling may also be possible.

Variant 2 (Fig. 4.20) and its two digesters, result in roughly 40% less slurry requiring further treatment than for Variant 1 (103,849 t/a). From Digester 2 7,652 tDM/a (60,659 t/a) digestate could be obtained, which can be applied directly as fertilizer, as it is considered “clean” substrate limited to agricultural waste inputs.

4.2.2 Economic Analysis

The developed DST is a universal tool to assist the integrated planning of environmental projects. The tool evaluates energy potentials, mineral recovery and wastewater reclamation, while providing a comprehensive economic analysis for any of 16 possible scenarios and two variants per scenario, based on user data inputs.

In the economic analysis, the DST estimates capital investment, operation and maintenance costs; projected revenues based on the input scenario; financial comparisons for centralized versus partially decentralized wastewater treatment; costs associated with phosphorus recovery and wastewater re-use; and cash-flow analysis and annuity plan, allowing the user to understand all aspects of financial planning and management.

Based on the input data of the Serbian CSR, expected costs and revenues of Variants 1 and 2 are summarized in the Tab. 4.11. As seen in Tab. 4.11, for the CSR input parameters, the highest proportion of investment cost is the wastewater treatment units followed by anaerobic digestion. Due to the inclusion of decentralized wastewater treatment units for Variant 2, investment costs are roughly 5% higher than for Variant 1. The introduction of phosphorus recovery, assuming by the Stuttgart process, increases total investment by ca. 2% for both variants, while effluent disinfection increases costs by 3% for Variant 1 and 5% for Variant 2. Despite the minimal increase in investment costs for phosphorus recovery, its related operation costs create the second-highest share of total annual O&M costs of ca. 25%, after considering the costs of slurry/digestate transport and disposal (30% for Variant 1 and 27% for Variant 2). Energy costs account for 16% of the total operation costs, and estimated labor 4%. Disinfection accounts for less than 1% of the total O&M costs.

Tab. 4.11: Expected costs and revenues for Variant 1 and 2 of Scenario d-4 for the tested CSR input data

			Scenario 1	Scenario 2
Expenses	Investment Costs	Wastewater treatment - WWTP	20,187.000 €	17,437,500 €
		Wastewater treatment units - SBR	-	2,550,000 €
		Wastewater treatment units - CW	-	5,120,000 €
		Digester 1	17,046,728 €	4,893,895 €
		Digester 2	-	12,061,898 €
		MAP Recovery	872,100 €	785,700 €
		Effluent disinfection WWTP	1,130,500 €	976,500 €
		Effluent disinfection SBR	-	312,000 €
		Effluent disinfection CW	-	832,000 €
		Total Investment Costs	**39,236,828 €**	**44,964,492 €**
	O&M Costs	Labour	144,000 €/a	144,000 €/a
		Electrical energy for wastewater treatment & digester	620,370 €/a	575,443 €/a
		MAP Recovery	929,550 €/a	829,350 €/a
		Effluent disinfection WWTP	17,702 €/a	15,291 €/a
		Effluent disinfection SBR	-	658 €/a
		Effluent disinfection CW	-	585 €/a
		Transport & dispoal of digestate	1,163,687 €/a	962,253 €/a
		Costs of chemicals	77,874 €/a	66,885 €/a
		Maintenenace	784,737 €/a	899,390 €/a
		Total O&M Costs	**3,728,737 €/a**	**3,494,853 €/a**
Revenues		Generated electricity	3,235,929 €/a	3,077,421 €/a
		Generated heat	1,035,191 €/a	1,020,656 €/a
		MAP	703,749 €/a	512,107 €/a
		Fertiliser (digestate of the digester 2)	-	606,592 €/a
		Income from wastewater tariffs	2,150.868 €/a	2,150.868 €/a
		Total Revenues	**7,125,737 €/a**	**7,246,326 €/a**

Revenues are derived from energy recovery, phosphorus recovery and tariffs. For the tested CSR, the highest proportion of revenue results from energy recovery (ca. 60%), followed by tariffs (30%), MAP recovery (10% Variant 1 and 7% Variant 2) and digestate that can be directly applied as a fertilizer in under Variant 2 (7%).

In the subsequent step, the DST provides a cash-flow analysis; for the tested CSR, it was assumed that the project would be financed with a loan in the amount of 90% of investment costs, with the balance of 10% provided from own municipal financing sources (Fig. 4.17) Assuming annual interest rate of 7% and 20 years repayment period, and given the inputted tariff values and 2014 utility cost figures (Fig. 4.17), and an assumed discount rate of 5%, the cumulative net present value over 20 years equates to ca. €0.8 Mil for Variant 1 and - €0.9 Mil. for Variant 2. Given utility price hikes since 2014, plus declining interest rates, the DST would provide different results in today’s environment. Thus, the DST provides decision-makers with an updatable tool to project, plan and finance integrated projects.

4.2.3 Comparative Analysis of Scenarios

The DST allows users to perform comparative assessments of two variants of a given scenario to consider centralized or decentralized treatment options based on user inputs. For the tested CSR, Tab. 4.12 presents the results of the comparative analysis of the two variants and the respective input data. At first glance, Variant 1 is likely to be more attractive to decision-makers due to its lower investment costs and positive cumulative net present value (NPV). However, the operational costs of Variant 2 are lower, plus it has higher annual revenues, which could be also prove a driving factor. Other criteria may be more important to different stakeholders as well. As Tab. 4.12 indicates, Variant 2 possesses some technical advantages over Variant 1 in terms of flexibility to adapt to changing conditions and flows, as it is modular and decentralized. Variant 2 can also be further augmented with additional decentralized units, or in the case of decreased flows, units may be switched off without affecting overall performance. In a decentralised concept, system failure is likely to be less damaging than in a centralized system. Although the operational complexity of both variants should not be underestimated, Variant 1 holds an advantage in this regard, as it would be easier to hire and train technical personnel through local labour markets.

Considering social criteria, acceptance by communities and users on the new treatment processes and infrastructure are estimated to be low, as this is not state-of-the-art technology. Here, Variant 1 may hold advantages, as it involves fewer treatment steps and operations which are more known in practice. When it comes to employment, both scenarios offer similar results, with Variant 2 offering additional employment due to its additional treatment options.

Considering environmental protection, Variant 2 holds advantages, as there are less residues requiring landfilling, and energy consumption is lower than for Variant 1. From an environmental perspective, the most significant advantage is the two valuable products produced under Variant 2: MAP and high-quality fertiliser from the output of Digester 2. Variant 1 does show slightly higher energy recovery potential, however, due to Variant 2's partial decentralisation operations for which energy cannot be recovered.

Administrative procedures for both variants are expected to be complex, as such concepts are not business-as-usual solutions, and administrative, regulatory and permitting challenges are sure to arise.

Tab. 4.12: Comparative Variants assessment for the tested CSR input data.

Criteria	**No.**	**Sub-criteria**	**Variant 1**	**Variant 2**
Technical	1.1	Flexibility/modularity	++	++++
	1.2	Operational complexity	++	++++
	1.3	Process stability & Robustness	++	+++
	1.4	Infrastructure adaptation	++	++++
Social	2.1	Public acceptance	++	+
	2.2	Employment Opportunities	+++	++++
Environmental	3.1	Landfilled residues	172,974 t/a	103,849 t/a
	3.2	Energy consumption	21,256 MWh/a	20,459 MWh/a
	3.3	Reagens consumption	86,526.4 t/a	74,316.1 t/a
	3.4	GHGs emissions savings	76,681 t/a	75,604 t/a
	3.5	Recovered energy (gross)	38,340 MWh/a	36,462 MWh/a
	3.6	Recovered materials	2,346 t MAP/a	1.767 t MAP/a; 56.795 t fertiliser/a
	3.7	Re-used water	8,429,493 m³/a	8,429,493 m³/a
Financial	4.1	Investment Costs	39,236,828 €	44,969,492 €
	4.2	O&M Costs	3,728,919 €/a	3,494,853 €/a
	4.3	Revenues	4,974,869 €/a	5,095,458 €/a
	4.4	NPV (Cumulative 20 years)	791,433	- 858,0003 €
Administrative	5.1	Complexity of authorization	+++	++++

4.2.4 Sensitivity of the DST

To determine the overall robustness of the DST a series of sensitivity analyses were executed, applying changes to the tested Scenario “d-4” and both variants.

The first sensitivity analysis focuses on changes in wastewater quantity for treatment. Thus, PE-value and the amount of wastewater to be treated were decreased and then increased by 10%. When applying these changes, the model results show near-linearity with respect to the PE value; as Tab. 4.13 shows, nearly all output values range within +/-10% given the 10% increase and decrease in flow. Reagent consumption and water re-use reach changes of +10% and -10% for the Variant 1 and Variant 2 retrospectively (Tab. 4.13). Only NPV displays a more significant change of 98% for Variant 1 and 89% for Variant 2 (Tab. 4.13). Interestingly, an increase of PE and corresponding 10% higher quantity of wastewater, nearly turns Variant 2 financially sound. Thus, it can be stated that the change in amount of wastewater to be treated (including estimated treatment capacity) is of significant importance when it comes to the overall performance of integrated projects.

Tab. 4.13: Sensitivity of the DST according to changes in PE and amount of wastewater to be treated

	Variant 1					Variant 2				
	Standard Value	Standard Value +10%	Change	Standard Value -10%	Change	Standard Value	Standard Value +10%	Change	Standard Value -10%	Change
Landfilled residues	172,974	182,090	5%	163,859	-5%	103,849	112,110	8%	95,587	-8%
Energy consumption	21,256	21,965	3%	20,547	-3%	20,459	21,098	3%	19,820	-3%
Reagens consumption	86,526	95,179	10%	77,874	-10%	74,316	81,748	10%	66,885	-10%
GHG savings	76,681	77,551	1%	75,810	-1%	75,604	76,367	1%	74,841	-1%
Recovered energy (gross)	38,340	38,776	1%	37,905	-1%	36,462	36,844	1%	36,081	-1%
Recovered materials	2,346	2,398	2%	2,294	-2%	1,767	1,767	0%	1,767	0%
Re-used water	8,429,493	9,272,442	10%	7,586,543	-10%	8,429,493	9,272,442	10%	7,586,543	-10%
Investment Costs	39,236,828	41,649,323	6%	36,824,333	-6%	44,969,492	47,940,429	7%	41,998,556	-7%
O&M Costs	3,728,919	3,945,764	6%	3,512,075	-6%	3,494,853	3,705,107	6%	3,284,598	-6%
Operation Revenues	4,974,869	5,038,921	1%	4,910,817	-1%	5,095,458	5,151,974	1%	5,038,942	-1%
NPV (20 years)	791,433	1,567,752	98%	15,114	-98%	-858,003	-93,464	89%	-1,622,542	-89%

The second sensitivity analysis focuses on bio-waste and agro-waste variances, where a +10% increase and a -10% decrease in available flows were applied. As can be seen in *Tab. 4.14*, reagent consumption and re-used water are uninfluenced by changes in biomass, as these are influenced only by the quantity of wastewater. All other parameters were altered by +/-4% (O&M Costs) up to +/- 9% (GHGs emissions savings, recovered energy, revenues) (Tab. 4.14). As in the previous analyses, the impact of the variation is most substantial on NPV. Increasing biomass by 10% changed the total cumulative NPV from 791,433 EUR to 4,427,685 EUR (+ 459%) in the case of Variant 1 and from -858,003 EUR to 3,232,079 EUR in the case of Variant 2 (Tab. 4.14). When decreasing the biomass quantity by 10% the NPV drops from 791,433 EUR to -2,844,818 EUR in Variant 1 and from to -858,003 EUR to -4.948.085 EUR (-447%) in Variant 2. Thus, biomass has the largest impact on the analysed outputs, especially in terms of financial feasibility of the envisaged integrated scenario (Tab. 4.14).

Tab. 4.14: Sensitivity of the DST to change of biomass quantity to be treated

	Variant 1					Variant 2				
	Standard Value	Standard Value +10%	Change	Standard Value -10%	Change	Standard Value	Standard Value +10%	Change	Standard Value -10%	Change
Landfilled residues	172,974	181,156	5%	164,792	-5%	103,849	105,972	2%	101,726	-2%
Energy consumption	21,256	22,673	7%	19,839	-7%	20,459	21,866	7%	19,053	-7%
Reagens consumption	86,526	86,526	0%	86,526	0%	74,316	74,316	0%	74,316	0%
GHGs emissions savings	76,681	83,478	9%	69,883	-9%	75,604	82,402	9%	68,807	-9%
Recovered energy (gross)	38,340	41,739	9%	34,942	-9%	36,462	39,727	9%	33,197	-9%
Recovered materials	2,346	2,528	8%	2,163	-8%	1,767	1,767	0%	1,767	0%
Re-used water	8,429,493	8,429,493	0%	8,429,493	0%	8,429,493	8,429,493	0%	8,429,493	0%
Investment Costs	39,236,828	40,748,001	4%	37,725,656	-4%	44,969,492	46,495,505	3%	43,443,480	-3%
O&M Costs	3,728,919	3,870,564	4%	3,587,274	-4%	3,494,853	3,619,684	4%	3,370,022	-4%
Operational Revenues	4,974,869	5,408,296	9%	4,541,442	-9%	5,095,458	5,548,488	9%	4,642,428	-9%
NPV (20 years)	791,433	4,427,685	459%	-2,844,818	N.A.	-858,003	3,232,079	N.A.	-4,948,085	-477%

The third analysis was conducted to determine the effect of applying Technical Standard ATV-DVWK-A-131E (ATV, 2000) on the overall results, compared to the derived inhabitants' pollutant loads based on performed measurements. Applying the inhabitant pollutants loads (ATV, 2000) as listed in Tab. 4.5 diminished landfill residues by 11% in the case of Variant 1 and by 16% in the case of Variant 2 (Tab.

4.15). Reagent consumption increased by 52% for both variants. All other results changed by -2% in both variants. Interestingly by applying the German norms, the cost estimates are ca 1% lower, while estimated revenues ca. 2% lower compared to the derived values. Only the NPV deviates from this observation, changing by more than -100% in Variant 1 and -84% in Variant 2 (Tab. 4.15).

Tab. 4.15: Sensitivity of the DST to change of design parameters

	Variant 1			Variant 2		
	Derived Serbian inhabitant-specific pollutant loads (Tab4.5. based on 85% fractile)	*German Technical Standard ATV-DVWK-A-131E*	Change	*Derived Serbian inhabitant-specific pollutant loads (Tab4.5. based on 85% fractile)*	*German Technical Standard ATV-DVWK-A-131E*	Change
Landfilled residues	172,974	153,555	-11%	103,849	87,075	-16%
Energy consumption	21,256	20,792	-2%	20,459	20,044	-2%
Reagens consumption	86,526	131,290	52%	74,316	112,982	52%
GHGs savings	76,681	74,823	-2%	75,604	73,999	-2%
Recovered energy (gross)	38,340	37,411	-2%	36,462	35,660	-2%
Recovered materials	2,346	2,346	0%	1,767	1,767	0%
Re-used water	8,429,493	8,429,493	0%	8,429,493	8,429,493	0%
Investment Costs	39,236,828	38,823,759	-1%	44,969,492	44,612,693	-1%
O&M Costs	3,728,919	3,691,318	-1%	3,494,853	3,463,515	-1%
Operational Revenues	4,974,869	4,871,373	-2%	5,095,458	5,006,061	-2%
NPV (20 years)	791,433	-29,758	N/A	-858,003	-1,581,557	-84%

The three conducted sensitivity analyses confirmed that obtained results are consistent with the primary analysis and would lead to the similar conclusions for a user working with the DST. Therefore, it may be stated that the DST is robust. Overall, the among performed sensitivity analysis, the WWTP design parameters (tested in the third sensitivity analysis; Tab. 4.15) appears to be the most sensitive. As Tab 4.15 shows that application of derived inhabitant specific loads in the DST is of significant importance when it comes to the overall performance estimation of analysed integrated concept. As the sensitivity analysis showed, the common application of international technical design parameters (in this case the German Technical Standard ATV-DVWK-A-131E) may lead to underestimation of disposal space and energy consumption, and especially the generated NPV, which may mislead the decision maker and result in discarding implementation of integrated project. Therefore, significance of conduction of case specific measurement campaign and derivation of inhabitants’ pollution loads is evident.

4.2.5 DST Limitations

The central focus of the DST is inter-connecting wastewater management with associated sectors defined by a common throughput (i.e., solid waste and agriculture sectors). Despite its universal cross-sectoral characteristic, the DST is primarily designed to assist stakeholders planning new or renovating wastewater infrastructure. With the DST, users can quantitatively compare advantages, costs and cross-sectoral synergies, with joint aims of nutrient, energy and water recovery and re-use and financial optimisation. Despite these capabilities, the DST does have certain limitations.

- The DST does not consider settlement structures and specifics, and thus cannot determine how to locally organise wastewater treatment. Prior to using the DST, the user should have certain knowledge of the planned type and capacities of wastewater treatment for the region. Furthermore, as explained in Chapter 3.3.3.1, the DST considers three possible treatment scenarios: 1) activated sludge treatment for a central WWTP; 2) SBR as a decentralised conventional option; and 3) constructed wetlands as a natural, decentralised option. Comparing technologies and treatment options outside these parameters is not possible with the present version of the DST.
- Flow collection and delivery of bio- and agro-waste are assumed to be managed and available, as the DST user inputs only quantities of separate waste flows. In practicality, as described in Chapter 2.2.2, many European localities are still are shifting towards waste source separation practices. In the

Serbia CSR, green cut is separately available, but its collection is not covered by the DST; the organic component of municipal solid waste is not currently separated or available in the CSR.

- The DST does not consider seasonal or future variations of organic flow rates or compositions. Practically, crops residues and green cut are only seasonally available, while municipal bio-waste and sewage sludge can also be prone to seasonal quantity and composition changes.
- With respect to energy recovery, it is assumed that electrical energy would be sold via feed-in tariff to the national electricity supplier, while thermal energy can likely be sold to one or more users in the nearby industrial zone. This is applicable for the tested CSR but may not be in countries with no feed-in tariff scheme or other obstacles. Furthermore, the DST does not compute infrastructure costs for any energy delivery option.
- The proposal to reuse the wastewater treatment effluent for irrigation is also not without practical and logistical challenges. The DST does not consider availability and costs for an irrigation pipeline network, nor challenges to land ownership and rights-of-way.
- The DST considers phosphorus recovery in the form of MAP via the Stuttgart Process. There are, however, other phosphorus recovery alternatives of varying technology-readiness levels as described in Chapter 2.3.3.1. Considering additional alternatives would require a DST upgrade.
- The DST does not account for public acceptance factors and constraints. This is especially important for phosphorus recovery, as farmers may resist using recovered MAP due to lack of information. A similar challenge would arise with respect to wastewater re-use for agriculture.
- Despite having robust financial capabilities, DST estimates should be considered preliminary for applicable only for those cases in line with the literature values assumed (Appendix 5). More intensive analysis is required for more precise cost estimation.
- To use the DST effectively, users should possess certain data and information necessary for all inputs, as well as the basics of existing and planned WWTP capacities and facilities.

Despite these limitations, the DST aims to provide decision-makers with a universally applicable tool whose input parameters can be changed to suit future needs as well. The “User Input Selection” worksheet (Tab 4.17) allows users to input parameters concerning utility prices and feed-in tariffs, project financing and user tariffs according to the specific case. The DST incorporates certain parameters based on literature values for the mass balance calculation (Appendix 4) and cost estimation (Appendix 5); these parameters may also be changed by the user, providing greater adaptability for diverse local conditions. In communities with no source separation practice, the DST could also serve as a motivating tool for leaders to steer efforts toward source separation in line with EC efforts to advance implementation throughout Europe.

5 Conclusion and Outlook

This research assesses the environmental, social and financial benefits of applying integrated concepts to achieve Circular Economy aims. To support this objective, a universal, easily deployable DST was developed. The DST assesses concepts that integrate wastewater treatment flows with organic flows from municipal and agricultural sources, seeking flow and treatment synergies that help optimize resource utilization.

Regional solutions and initiatives offer good opportunities to apply transitional steps toward Circular Economy and applying innovative, cross-sectoral waste solutions. Applying new technologies and schemes could also open financing opportunities for the region, thereby fostering the well-being of citizens. To respond to our research questions, having a case study CSR was an important part of the research. Firstly, the CSR helped during the development process of the tool, and once the DST was finalized the results of the filed investigations were used to test the tool functionality. The results of the tested CSR demonstrate how integrated solutions can contribute to Circular Economy principles at the local level by quantifying potentials of energy generation, phosphorus recovery and water re-use.

The fundamentals of a decision-making process for integrated solutions were developed and tested in this research. The DST allows users to compare centralized versus partially decentralized, or modular variants of sixteen possible integrated waste treatment scenarios. The DST also provides a preliminary cost-benefit analysis and cumulative net present value for all scenarios and variants. While the DST was tested based on the Serbia CSR, it may potentially be used anywhere in the world, subject to additional case study testing and replicability. The most applicable regions for the DST are those in transition countries, where the main driver for integrated projects is a lack of environmental infrastructure and where potential constraints for such projects are expected to be minimal. As observed in the Serbia CSR, unsustainable resources management and poor environmental infrastructure is obvious, while legislative frameworks and financing abilities (e.g., EU pre-accession funding) for implementing innovative solutions are positive. Thus, the DST would have significant application for Serbian local condition as well as the other EU candidate and potential candidate members states mainly located in SEE (North Macedonia, Montenegro, Albania, Bosnia and Herzegovina) and east Europe (Moldova and Ukraine) which are facing similar socio-economical and environmental conditions like Serbia. In addition, the DST application is also highly suitable and may be of interest for the new EU member states which are significantly lacking behind the EU environmental standards (e.g. Croatia, Romania and partly Bulgaria and Hungary) as well as some old member states with poor environmental management (such as Malta, Cyprus). In the case of the old EU member states, the DST can also be applied although strongly developed and rigid single-sectoral infrastructure is the main obstacle. Nevertheless, for newly planned residential areas that will rely on decentralised infrastructure, the DST may also be useful. In the case of developing countries, DST may also be applicable, although in those cases, other challenges such as lack of financing opportunities and insufficient legislative frameworks are expected to be the main bottlenecks for integrated projects implementation.

The research showed that the DST is useful in the early stages of planning, as it invokes issues concerning engineering, environmental, financial and social aspects relevant to decision-makers. The DST's main strengths include:

- The DST helps decision-makers to obtain holistic knowledge of own organic material waste flows, their potential for energy and nutrient recovery, possible valorisation pathways, and preliminary financial estimates.
- The DST offers quantitative and qualitative comparisons of sixteen possible scenarios based on phosphorus and energy recovery and water re-use and two variants based on centralized versus modular treatments of sequence batch reactor (SBR) and/or constructed wetlands (CW).
- The DST is unbiased, as it only assesses scenarios, providing decision-makings with valuable data on which to base decisions.
- The DST is user-friendly and not time-consuming to learn or use, providing easily understandable, comparative results.
- The DST provides graphic visualizations of treatments, including associated material and energy inputs and outputs.

This research also provides insight into the level and type of input data needed to use the DST. For the applied CSR, data was obtained from extensive desk research by gathering official statistical records, complemented by a specific measurement campaign and surveys. Sensitivity testing the DST demonstrated that revising input values within a normal range still resulted in the tool performing properly with logical results. This is important, as it is unlikely that communities will have the human and financial resources to conduct extensive data collection, such as was done by this research.

The main advantage of applying integrated waste solutions is more efficient resource utilization of available flows and recovery of materials and energy that reduce the financial burden on end-users and advance Circular Economy goals. Based on this research, strong environmental policies are necessary for success of integrated projects. While the starting point lies with wastewater, the most important drivers for integrated projects include waste management policy and harmonization with Circular Economy principles, with landfill closure and organic waste disposal bans (2030) the main requisite. A new Circular Economy Action Plan (2020) emphasizing the importance of market development for recovered nutrients may also help to advance integrated projects.

Despite of the extensive effort conducted for this research, it is only a start to a process of continuing to improve and develop the methodology and its application. While the research and DST demonstrate the capabilities and usefulness of the DST, it also raises questions about its extension and adaptability for other cases; Chapter 4.2.5. outlines certain limitations of the tool for user consideration. To better understand the implications of the DST results, future case studies might address alternative decentralised treatment and recovery technologies, as well as seasonal and future dynamics of organic flows. Stakeholder cooperation and a holistic approach to integrated management is a prerequisite for success, as is a good understanding of public perception to identify social barriers and gain acceptance. Assessments of public attitudes and knowledge regarding integrated concepts can also assist policymakers, regulators, and practitioners. These and other areas are all possible subjects for further research.

This research demonstrated the ability of the DST as an attractive, user-friendly tool to support decision-making in planning and conceptual phases. It helps decision-makers to better underhand and evaluate the potentials of currently unused resources and transform them into new, usable products, providing a practical example to achieve Circular Economy on a local level. The DST is provided with this research and is available for further application and testing.

6 List of References

Abu-Ghunmi, D., Abu-Ghunmi, L., Kayal, B., and Bino, A. (2016) Circular economy and the opportunity cost of not ‘closing the loop’ of water industry: the case of Jordan. Journal of Cleaner Production 131 (10), 228-236.

Abwasserverband Zirl (http://www.green-foods.eu/best-practice/); Web 16 Apr 2018

AbfKlärV (2017) Verordnung zur Neuordnung der Klärschlammverwertung (Klärschlammverordnung – AbfKlärV); BGBl. I S. 3465, Bonn, 27.09.2017

Al-Saidi, M., Elagib, A.N. (2017) Towards understanding the integrative approach of the water, energy and food nexus. Science of the Total Environment 574, 1131-1139.

Al Seadi, T., Kirsten, G., Holm-Nielsen, B., J. (2000) Danish Centralised Biogas Plants - Plant Descriptions. Bioenergy Department, University of Southern Denmark, Torben Skøtt, BioPress.

Allan, T., Keulertz, M., Woertz, E. (2015) The water-food-energy nexus: an introduction to nexus concepts and some conceptual and operational problems. International Journal of Water Resources Development 31 (3), 301-311.

Angelidaki I., Batstone, D.J., Keller J., Kalyuzhny S.V., Pavlostathis, S.G., Rozzi A., Sanders W.T.M., Siegrist H., and Vavilin V.A. (2002) The IWA Anaerobic digestion model no 1. (ADM1)*, Wat. Sci. Technol*., 45, pp. 65-73.

Bernstad, A, la Cour Jansen, J. (2012) Review of comparative LCAs of food waste management systems - Current status and potential improvements, Waste Management, Volume 32, Issue 12, p.2439-2455.

Bajic B. Z., Dodic, S. N., Vucurovic, D. G., Dodic, J. M., Grahovac, J., A (2015) Waste to energy status in Serbia. Renewable and Sustainable Energy Reviews, 50, 1437-1444.

Banjac, M., Ramic, B., Lilic, D., Pantic, A. (2013) Energy in Serbia 2013, Republic of Serbia The Ministry of Mining and Energy, Department for strategic planning in energy sector. Available at: http://www.mre.gov.rs/doc/efikasnost-izvori/Brosura%20Energija%20u%20Srbiji%202013_%20ENERGY%20IN%20SERBIA%202013.pdf

Bajramović, N., Bogdanov, J. Butković, D. Dimitrievski, E. Erjavec, G. Gjeci, E. Gjokaj, B. Hoxha, I.J. Stomenkovska, D. Konjević, A. Kotevska, A. Martinović, I. Miftari, M. Nacka, D. Ognjenović, M. Rednak, E. Tuna, T. Volk, E. Zhllima (authors); Volk, T., E. Erjavec, P. Ciaian and S. Gomez y Paloma (editors) (2016). Analysis of the agricultural and rural development policies of the Western Balkan countries. EUR 27898 EN, Joint Research Centre, European Commission, doi:10.2791/744295.

Barquet, K., Linn J, Rosemarine, A., Macura, B. (2020) Identifying barriers and opportunities for a circular phosphorus economy in the Baltic Sea region. Water Research, 171. https://doi.org/10.1016/j.watres.2019.115433

Bertanza, G., Canato, M., & Laera, G. (2016). Ranking sewage sludge management strategies by means of Decision Support System: A case study. Resources, Conservation and Recycling 110, 1-5.

Bertanza, G., Canato, M., & Laera, G. (2018). Towards energy self-sufficiency and integral material recovery in wastewater treatment plants: Assessment of upgrading options. Journal of Cleaner Production, 170, 1206-1218. Doi: 10.1016/j.jclepro.2017.09.228

BMU (2017) Deutschland soll Phosphor aus Klärschlamm gewinnen, Pressemitteilung Nr. 017.

BMU, BMZ (2012). Bonn2011 Conference, The Water, Energy and Food Security Nexus, Solutions for a Green Economy: Policy Recommendations. Available at: https://www.water-energy food.org/fileadmin/user_upload/files/documents/bonn2011_policyrecommendations.pdf

Bogdanov, N., Rodić, V. (2014): Agriculture and Agricultural Policy in Serbia, Chapter B.VII in: Agricultural Policy and European Integration in Southeastern Europe Ed. by Volk, T., Erjavec E., Mortensen, K., FAO, Budapest, Hungary, pp. 153- 171, ISBN 978-92-5-108612-4/17.

Bogdanov, N., Rodić, V., Vittuari, M. (2017): Structural change and transition in the agricultural sector: Experience of Serbia, Communist and Post-Communist Studies, Volume 50, Issue 4, 319-330. https://doi.org/10.1016/j.postcomstud.2017.10.002

Bolzonella D., Battistoni P., Cecchi, F. (2006) Anaerobic co-digestion of waste activated sludge and OFMW: the experiences of Viareggioand Treviso plants (Italy). WaterSciTechnol 53, 203–211.

Bolzonella, D., Fatine, F., Gottardo, M., Frisona, N. (2018) Nutrients recovery from anaerobic digestate of agro-waste: Techno-economic assessment of full-scale applications. Journal of Environmental Management (216), 111-119. DOI: 10.1016/j.jenvman.2017.08.026

Blank, A.,Hoffmann, E. (2011) Upgrading of a co-digestion plant by implementation of a hydrolysis stage. Waste Management and Research 29 (11) 45–52. DOI: 10.1177/0734242X11423954

Björn, A., Sepehr, S.Y., Ziels, R.M., Gustafsson, K., Svensson, B.H., Karlsson, A., (2017) Feasibility of OFMSW co-digestion with sewage sludge for increasing biogas production at wastewater treatment plants. Euro-Mediterranean J. Environ. Integr. 2. https://doi.org/10.1007/s41207-017-0031-z

Breach, P. A., Simonovic, S. P. (2018) Wastewater treatment energy recovery potential for adaptation to global change: an integrated assessment Environmental Management 61 (4) 624–636.

Breisha, Z. G. (2010) Bio-removal of nitrogen from wastewater - A review. Nature and Science 8(12) 210-228.

Buekens, A. (2005) Energy recovery from residual waste by means of anaerobic digestion technologies. Conference: The future of residual waste management in Europe

BVR Radeberg (http://www.bvr-radeberg.de/anlage/) Web 17 Apr 2018

Cabbi, V., Bortoli, N.D., Goi, D. (2016) Pilot plant experience on anaerobic co-digestion of source selected OFMSW and sewage sludge. Waste Management 49, 47-54.

Case, S., Oelofse, M., Hou, Y., Oenema, O., Jensen, L., 2017. Farmer perceptions and use of organic waste products as fertilisers - a survey study of potential benefits and barriers. Agric. Syst. 151, 84e95. https://doi.org/10.1016/j.agsy.2016.11.012.

Cavinato, C., Bolzonella, D., Pavan, P., Fatone, F., Cecchi, F. (2013) Mesophilic and thermophilic anaerobic co-digestion of waste activated sludge and source sorted biowaste in pilot- and full-scale reactors. Renewable Energy (55) 260-265.

Cecchi, P., Cavinato, C. (2015) Anaerobic co-digestion and wastewater treatment. In: 3rd International Conference on Sustainable Solid Waste Management, Greece; July 2-4, 2015.

Cecchi, P., Cavinato, C. (2019) ASmart approaches to Food Waste Final Diposal. International Journal of Environmental Research and Public Health. Aug 10;16(16):2860. doi: 10.3390/ijerph16162860

Christodoulou, A., Stamatelatou, K. (2016) Overview of legislation on sewage sludge management in developed countries worldwide, Water Science and Technology, 73 (3), 453-462.

Cordell, D., Drangert, J.O., White, S. (2009). The story of phosphor: Global food security and food for thought. Global Environmental Change, 19(2) 292–305.

Cordell, D., White S., Lindström T. (2011) Peak phosphorus: the crunch time for humanity. The Sustainable Review.

Cornel, P., Meda, A., Bieler, S. (2011) Wastewater as a Source of Energy, Nutrients and Service Water. Earth Systems and Environmental Sciences, Treaties on Water Science, 4, 337-375.

Cornel, P., Schaum, C. (2009) Phosphorus recovery from wastewater: needs, technologies and costs. Water Science and Technology, 59 (6), 1069-1076.

Cvetkovic S., Kaludjerovic Radoicic T., Vukadinovic B. and Kijevcanin M. (2014) Potentials and status of biogas energy sources in the Republic of Serbia. Renewable and Sustainable Energy Reviews, Volume 31, 407-416.

Daigger, G.T., Murthy, S., Love. N.G., Sandino, J. (2017) Transforming Environmental Engineering and Science Education, Research, and Practice. Environmental Engineering Sciences, Journal 34(1), 42-50.

de Boer, M., Romeo-Hall, A., Rooimans, T., Slootweg, J. (2018) An assessment of the drivers and barriers for the deployment of urban phosphorus recovery technologies: a case study of The Netherlands. Sustainability 10. https://doi.org/ 10.3390/su10061790.

Desloover J., Vlaeminck S. E., Clauwaert P., Verstraete W. and Boon N. (2012). Strategies to mitigate N_2O emissions from biological nitrogen removal systems. Current Opinion Biotechnology (23), 474–482.

Deutscher Bundestag (1994) Bericht der Enquete Kommission – „Schutz des Menschen und der Umwelt“, Drucksache 12/8260.

Dimkic, D., Milovanovic, M. Dimkic, M., Miljkovic, S. (2020) Current and economic Prices of water in Serbia. Environ. Sci. Proc. 2020, 2(1), 45 https://www.mdpi.com/2673-4931/2/1/45

Dodic, N.S., Zekic, N. V., Rodic, O. V., Tica, Lj.N., Dodic, M.J. (2010) Situation and perspectives of waste biomass application as energy source in Serbia, Renewable and Sustainable Energy Reviews 14, 3171–3177.

Dominguez., Gujer, W. (2006) Evolution of a wastewater treatment plant challenges traditional design concepts**.** Water Res., 40 (2006),1389-1396.

Drenkova-Tuhtan, A., Schneider, M., Mandel, K., Meyer, C., Gellermann, C., Sextl, G., Steinmetz, H. (2016) Influence of cation building blocks of metal hydroxide precipitates on their adsorption and desorption capacity for phosphate in wastewater – A screening study, Colloids and Surfaces A: Physicochemical and Engineering 488, 145-153.

Djurisic-Mladenovic, N., Kiss, F., Skrbic, B., Tomic, M., Mici, R., Predojevic, Z. (2018) Current state of the biodiesel production and the indigenous feedstock potential in Serbia, Renewable and Sustainable Energy Review, 81 (1), 290-291. doi:10.1016/j.rser.2017.07.059

DWA (2006a) Arbeitsblatt DWA A-262. Grundsätze für Bemessung, Bau und Betrieb von Pflanzenkläranlagen mit bepflanzten Bodenfiltern zur biologischen Reinigung kommunalen Abwassers, DWA, Hennef.

DWA (2006b) Abwasserbehandlung - Gewässerbelastung, Bemessungsgrundlagen, Mechanische Verfahren, Biologische Verfahren, Reststoffe aus der Abwasserbehandlung, Weitergehende Abwasserreinigung - Weiterbildendes Studium "Wasser und Umwelt", Bauhaus-Universität Weimar, Weimar.

DWA (2008): Neuartige Sanitärsysteme. Hrsg. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef

DWA (2013) Regelwerk Merkbaltt DWA-A 205: Desinfektion von biologisch gereinigtem Abwasser, Hrsg. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef.

DWA (2014) Principles for the Planning and Implementation of New Alternative Sanitation Systems (NASS) Hrsg. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V., Hennef.

Egle, L., Rechberger, H., Krampe, J., Zessner, M. (2016) Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies, Science of The Total Environment 571, 522-542.

EC (2019) Regulation 2019/1009 of the European Parliament and od the Council of EU fertilizing products and amending Regulation (EC) No. 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. Official Journal of the European Union L 170/1. Available at: https://eur-lex.europa.eu/eli/reg/2019/1009/oj

EC (2008) Directive 2000/60/EEC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy of the European Parliament. Available https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32000L0060

EC (2008) Directive 2008/98/EC of the European Parliament and of the Council on Waste. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008L0098&from=EN

EC (2009) Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Available at: https://eur-lex.europa.eu/legalcontent/EN/TXT/HTML/?uri=CELEX:32009L0028&from=EN

EC (2011) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Roadmap to a Resource Efficient Europe. Brussels: COM 571, final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0571&from=EN

EC (2012) Manifesto for Resource-Efficient Europe. Available at: http://europa.eu/rapid/press-release_MEMO-12-989_en.htm

EC (2014a) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Towards a Circular Economy: A zero waste programme for Europe. Brussels: COM 398, final. Available at: http://ec.europa.eu/environment/circular-economy/pdf/circular-economy-communication.pdf

EC (2014b) Report on critical raw materials for the EU. Report of the Ad hoc Working Group on defining critical raw materials, May 2014 Available at: http://www.catalysiscluster.eu/wp/wp-content/uploads/2015/05/2014_Critical-raw-materials-for-the-EU-2014.pdf

EC (2015) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Closing the loop – An EU action plan for the Circular Economy. Brussels: COM 614, final. Available at: https://ec.europa.eu/transparency/regdoc/rep/1/2015/EN/1-2015-614-EN-F1-1.PDF

EC (2017a) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, The role of waste-to-energy in the circular economy. Brussels: COM 34, final. Available at: http://ec.europa.eu/environment/waste/waste-to-energy.pdf

EC (2017b) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Nineth Report on the implementation status and the programmes for implementation (as required by Article 17) of Council Directive 91/271/EEC concerning urban waste water treatment. Brussels: COM 749, final. Available at: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2017:0749:FIN:EN:PDF

EC (2017c) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on the 2017 List of Critical Raw Materials for the EU. Bussel: COM 490, Final. Available at: https://ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-490-F1-EN-MAIN-PART-1.PDF

EC (2018) EU ambassadors approve new rules on waste management and recycling, Press release 76/18 from 23.02.2018. Available at: https://www.consilium.europa.eu/en/press/press-releases/2018/02/23/eu-ambassadors-approve-new-rules-on-waste-management-and-recycling/

EC (2019) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, The European Green Deal. Brussels: COM 640, final. Available at: https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

EC (2020a) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A new Circular Economy Action Plan. For a cleaner and more competitive Europe. Brussels: COM 98, final. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

EC (2020b) Commission Staff Working Document, Serbia 2020. Report Accompanying the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions 2020 Communication on EU Enlargement PolicyEurope. Brussels: SWD 352, final. Available at: https://ec.europa.eu/neighbourhood-enlargement/sites/near/files/serbia_report_2020.pdf

EEA (2011) Waste – State and Impact Serbia. Available at: https://www.eea.europa.eu/soer/countries/rs/waste-state-and-impacts-serbia

EEA (2016) Municipal waste management across European countries. Available at: https://www.eea.europa.eu/themes/waste/municipal-waste

EEA (2017) Urban waste water treatment. Available at: https://www.eea.europa.eu/data-and-maps/indicators/urban-waste-water-treatment/urban-waste-water-treatment-assessment-4

Egle, L., Rechberger, H., Krampe, J. and Zessner, M. (2016) Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies, Science of The Total Environment, Volume 571, 522-542.

EIB (2017) The EIB in the circular economy. Available at: http://www.eib.org/attachments/thematic/circular_economy_en.pdf

Elsner, H. (2008) Stand der Phosphat-Reserven weltweit. In Braunschweiger Nährstofftage 2008. Braunschweig: Bundesanstalt für Geowissenschaften und Rohstoffe, 2008.

Ellen MacArthur Foundation (2013) Towards the Circular Economy, Opportunities for the Consumer Goods Sector.

Endo, A., Tsuria, I., Burnett, K. Orencio, M.P (2017). A review of the current state of research on the water, energy and food nexus. Journal of Hydrology: Regional Studies 1, 20-30.

EP (2017a) Circular economy package: Four legislative proposals on waste, Briefing, EU legislation in Progress. Available at: http://www.europarl.europa.eu/RegData/etudes/BRIE/2017/599288/EPRS_BRI%282017%29599288_EN.pdf

EP (2017b) Towards a circular economy – Waste management in the EU. Available at: http://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_STU%282017%29581913

EP (2020) Drinking water in the EU: better quality and access. Accessed at 08.12.2020 https://www.europarl.europa.eu/news/en/headlines/society/20181011STO15887/drinking-water-in-the-eu-better-quality-and-access

EPA (2004) Technical Development Document for the Final Effluent Limitations Guidelines and Standards for the Meat and Poultry Products Point Source Category (40 CFR 432).

EPA (2000) Manual: *Constructed Wetlands Treatment of Municipal Wastewaters*, EPA/625/R-99/010, Ohio, 2000.

Eriksson, M., Strid, I., Hansson, P, A. (2015)_Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study. Journal of Cleaner Production., 93, 115-125.

European Council (1991) Council Directive 1991/271/EEC concerning urban waste water treatment. Official Journal of European Community L135/40. Available at: https://eur-lex.europa.eu/legal content/EN/TXT/HTML/?uri=CELEX:31991L0271&from=EN

European Council (1991) Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official Journal of European Community L375. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31991L0676&from=EN

European Council (1999) Council Directive 1999/31/EC on the landfill of waste. Official Journal L182, 16/07/1999. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:31999L0031&from=EN

Eurostat http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do, Web 28. Nov 2018

Evans, G. (2001) Biowaste and Biological Waste Treatment. James & James, London.

FAO (2020) Smallholders and family farms in Serbia. Country study report 2019. Budapest. https://doi.org/10.4060/ca7449en

Fachverband Biogas (2016) Biowaste to Biogas, Freising.Available at: https://biowaste-to-biogas.com/Download/biowaste-to-biogas.pdf

Fijalkowski, K., Rorat, A., Grobelak, A., Kacprzak, M.J. (2017) The presence of contaminations in sewage sludge - the current situation. Journal of Environmental Management 203 (2017) pp. 1126-1136.

Foladori, P., Vaccari, M., Vitali, F. (2015) Energy audit in small wastewater treatment plants: methodology, energy consumption indicators, and lesson learned. Water Science and Technology. 72, 1007-1015.

Flanders (2017) Water Sector in Serbia. Invest and trade market survey. Embassy of Belgium.

FRN, Fachagentur Nachwachsende Rohstoffe e.V (2016) Leitfaden Biogas. Von der Gewinnung zur Nutzung. Available at: https://www.fnr.de/fileadmin/allgemein/pdf/broschueren/Leitfaden_Biogas_web_V01.pdf

Fankhauser, S., Tepic, S. (2007), Can Poor Consumers Pay for Energy and Water? An Affordability Analysis for Transition Countries, Energy Policy 35 (2) 1038-1049.

GAIN (2015) Serbian Agriculture Overview and Best Prospects- 2015 (RB1504). Available at: https://www.deutsche-melasse.de/wp/wp-content/uploads/2015-06.06-Serbia-Agriculture-Overview-and-Best-Prospects.pdf

Ganora, D.; Hospido, A.; Husemann, J.; Krampe, J.; Loderer, C.; Longo, S.; Moragas Bouyat, L.; Obermaier, N.; Piraccini. E.; Satnev, S.; Váci, L.; Pistocchi, A. (2019) Opportunities to improve energy use in urban wastewater treatment: a European-scale analysis Environ. Res. Lett. 14.

Gauff Ingenieure, Setec E&C, Setec. (2012) Final Feasibility Study Report - Wastewater Collection and Treatment Krusevac.

Genovese, A., Acquaye, A., A. Figueroa, A., Koch, S.C.L. (2017) Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications, Omega, 66 (B), 344-357.

GIZ (2017) Waste-to-Energy Options in Municipal Solid Waste Management - A Guide for Decision Makers in Developing and Emerging Countries, Eschborn.

Gray, N. F. (2005) Nature of Wastewater, Water Technology: An Introduction for Environmental Scientists and Engineers, 2, 349–367.

GRS (2011) National Environmental Approximation Strategy, Belgrade. Available at: http://www.misp-serbia.rs/wp-content/uploads/2010/05/EAS-Strategija-ENG-FINAL.pdf

GRS (2013) National Renewable Energy Action Plan of the Republic of Serbia, Belgrade. Available at: http://www.mre.gov.rs/doc/efikasnost-izvori/NREAP%20OF%20REPUBLIC%20OF%20SERBIA%2028_June_2013.pdf?uri=CELEX:32009L0028

GRS (2014) Serbian Energy Development Strategy to 2025, with projections to 2030. Available at: http://www.parlament.gov.rs/upload/archive/files/lat/pdf/akta_procedura/2014/113-14Lat.pdf

GRS (2015a) The Water Management Strategy of the territory of the Republic of Serbia, Belgrade, Available at: http://www.rdvode.gov.rs/doc/Strategija%20upravljanja%20vodama.pdf

GRS (2015b) Government of the Republic of Serbia (b), The Transposition and Implementation of Environmental and Climate Change Acquis – Chapter 27: Status and Plans, Belgrade, Available at: http://www.pregovarackagrupa27.gov.rs/?wpfb_dl=71

GRS (2016) Energy Sector Development Strategy of the Republic of Serbia

for the period by 2025 with projections by 2030. https://www.mre.gov.rs/doc/efikasnost-izvori/23.06.02016%20ENERGY%20SECTOR%20DEVELOPMENT%20STRATEGY%20OF%20THE%20REPUBLIC%20OF%20SERBIA.pdf

Gude, V. G. (2015) Energy and water autarky of wastewater treatment and power generation systems Renew. Sustain. Energy Rev. 45, 52–68.

Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.B., Daigger,, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., Macpherson, L., Mihelcic, J.R., Pramanik, A., Raskin, L., Van Loosdrecht, M.C.M., Yeh, D., Love, N.G. (2009) A new planning and design paradigm to achieve sustainable resource recovery from wastewater. Environ. Sci. Technol. 42(16), 6126–6130 (2009).

Gujer, Willi (2007): Siedlungswasserwirtschaft. 3., bearb. Aufl.,Springer-Verlag.

Hagos, K., Zong, J., Li, D., Liu, C., Lu. X. (2017) Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. Renewable and Sustainable Energy Reviews, 76,1485-1496. https://doi.org/10.1016/j.rser.2016.11.184.

Hamelin, L., Borzecka, M., Kozak, M., Pudeolo, R. (2019) A spatial approach to bioeconomy: Quantifying the residual biomass potential in the EU-27. Renewable and Sustainable Energy Reviews 100, 127–142.

Hammer, M., Giljum, S., Bargigli, S., & Hinterberger, F. (2003) Material Flow Analysis on the Regional level: Questions, Problems, Solutions. NEDS Working Paper. No. 2, 04/2003, Hamburg.

Haskoning Nederland B.V. Water, Ihs Institute For Housing And Urban Development Studies, Deloitte&Touche Central Europe (2007a)., Feasibility Study Vrbas, Waste Water Treatment and Sewage collection.

Haskoning Nederland B.V. Water, Ihs Institute For Housing And Urban Development Studies, Deloitte&Touche Central Europe (2007b) Feasibility Study Leskovac Wastewater Collection & Treatment Water Supply Extension.

Haskoning Nederland B.V. Water, Ihs Institute For Housing And Urban Development Studies (2007c)., Feasibility Study Šabac Waste Water Treatment Project.

Held J., Mathiasson A., Nylander A. (2008) Biogas from manure and waste products – Swedish case studies. Stockholm, Sweden: Swedish Gas Centre; Swedish Gas Association; Swedish Biogas Association.

Henze, M., Loosdrecht, M.C.M, Ekama, G.A., Brdjanovic, D. (2008). Biological Wastewater Treatment: Principles, Modelling and Design. IWA Publishing

Henze, M., Harremoes, P., Cour Jansen, J. la, Arvin, E. (2002). Wastewater Treatment: Biological and Chemical Processes. Springer Science & Business Media

Hering, J., G., Waite, D., T.., Richard, L., Drewes, J. E., Sedlak, D., L. A Changing Framework for Urban Water System, Environ. Sci. Technol. 47, 10721-10726.

Hoff, H. (2011) Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm. Available at: http://wef-conference.gwsp.org/fileadmin/documents_news/understanding_the_nexus.pdf

Holliger C., Fruteau de Laclos H., Hack G. (2017) Methane Production of Full-Scale Anaerobic Digestion Plants Calculated from Substrate’s Biomethane Potentials Compares Well with the One Measured On-Site. Front. Energy Res. 5:12.

Horstmeyer, N., Rapp-Fiegle, S., Helmreich, B., Drewes, J.E. (2014) Kosten der Abwasserbehandlung. Finanzierung, Kostenstrukturen und Kostenkenndaten der Bereiche Kanal, Sonderbauwerke und Kläranlagen’. Deutscher Industrieverlag GmbH, Munich.

Husmann, M. (2009) Improving energy efficiency in wastewater treatment plants: What emerging countries can learn from experience gained in the developed world. Water Week conference, 17.02.2009.

Husemann, J., Steinmetz, H., Hempfling, C., Maksimovic, A. (2018) Synthesis centers on innovative wastewater treatment. Case Study Serbia EUR 29278 EN, Publications Office of the European Union, Luxembourg, 2018

Huygens D., Saveyn HGM., Tonini D., Eder P., Delgado Sancho L. (2019) Technical proposals for selected new fertilising materials under the Fertilising Products Regulation (Regulation (EU) 2019/1009) - Process and quality criterion, and assessment of environmental and market impacts for precipitated phosphate salts & derivates, thermal oxidation materials & derivates and pyrolysis & gasification materials, EUR 29841 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-09888-1, doi:10.2760/186684, JRC117856.

Hwang, M. H., Jang, N. J., Hyum, S. H. and Kim, I. S. (2004) Anaerobic bio-hydrogen production from ethanol fermentation: the role of pH. Journal of Biotechnology, 111 (3), 297-309.

Iacividou, E., Voulvoulis, N. (2012) Food waste co-digestion with sewage sludge – Realising its potential in the UK. Journal of Environmental Management 112, 267-274.

ICPDR (2015) The Danube River Basin District Management Plan. Part A – Basin wide overview. ICPDR, Vienna.

International Water Association and Romanian Water Association (2016) Water Tariffs and Affordability: Future options for the tariff strategies in Romania.

IWR - Internationales Wirtschaftsforum Regenerative Energien http://www.iwr.de/bio/biogas/Checkliste-Biogas-Anlage.html (retrieved July 2017)

JCI (2011) Water Management Plan for the Danube River Basin. Part 1: Analysis of the Danube River Basin Characteristics in Serbia, Belgrade.

Kabbe (2017) Overview of phosphorus recovery from the wastewater stream facilities operating or under construction. https://www.phosphorusplatform.eu/images/download/Kabbe_Tech_implementation-Table_20170208.pdf

Kaseng, K., Ibrahim, K., Paneerselvam, S. V. and Hassan, R. S. (1992) Extracellular enzyme and acidogen profiles of a laboratory-scale two-phase anaerobic digestion system. Process Biochemistry, 27, 43-47.

Karovic Maricic,V., Danilovic,D., Lekovic, B., Crnogorac,M.+(2018) Energy policy reforms in the Serbian oil sector: An update. Energy Policy 113, 348-355. https://doi.org/10.1016/j.enpol.2017.11.011

Kirchherr, J., Reike, D., Hekkert, M. (2017) Conceptualizing the circular economy: An analysis of 114 definitions, Resources, Conservation and Recycling (127) 221-232.

Koch, K., Plabst, M., Schmidt, A., Helmreich, B., Drews, J. (2016) Co-digestion of food waste in municipal wastewater treatment plant: Comparison of batch tests and full-scale experiments. Waste Management 47, 28-33.

Krampe, J., Willis, M., Richards. D. (2010) Co-digestion of high strength organic trade waste with wastewater sludge. Water (Australia) 37; 56 – 60.

KrW-/AbfG (1994) Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Beseitigung von Abfällen (Kreislaufwirtschafts – und Abfallgesets, KrW-/AbfG) BGBL Jahrgang 1994, Nr. 66, Bonn, 06. 10. 1994

Klass, D. L. (1984) Methane from Anaerobic Fermentation. Science.A, 223, (4640), 1021-1028.

Kläranlage Mossburg (https://klaeranlage-moosburg.de/die-zahlen-der-klaranlage/); Web 16 Apr 2018

Korhonen, J., Honkasalo, A., Seppälä, J. (2018) Circular Economy: The Concept and its Limitations, Ecological Economics, 143, 37-46.

Kurobe WWTP (https://www.swing-w.com/eng/solution/kurobe_p.html) Web 18 Apr 2018

Larsen, T.A., Gujer, W. (1997) The concept of sustainable urban water management. Water Sci. Technol, 37(9) 3–10, 1997.

Liu, Y., Hejazi, M., Kyle, P., Kim, S. H., Davies, E., Miralles, D. G., Teuling, A. J., He, Y., Niyogi, D. (2016) Global and regional evaluation of energy for water Environ. Sci. Technol. 50 (17), 9736–45.

Long, D. N, Koch, K., Bolzonella, D., Drewes, J. (2017) Full scale co-digestion of wastewater sludge and food waste: Bottlenecks and possibilities. Renewable and Sustainable Energy Reviews 72, 354-362.

Lu, J., Ahring, B. K. (2007) Optimization of Anaerobic Digestion of Sewage Sludge Using Thermophilic Anaerobic Pre-Treatment Technical University of Denmark, Copenhagen.

Lüderitz V., Eckert E., Lange-Weber M., Lange A. and Gersberg R.M. (2001) Nutrient removal efficiency and resource economics of vertical flow and horizontal flow wetlands, Ecol. Eng.18, pp 157-171.

Maabjerg Energy Center (www.maabjergenergycenter.dk/) (2018); Web 14. April 2018

Massey, M.S., Davis,J.G., Ippolito, J.A., Sheffield, R.E. (2009) Effectiveness of recovered magnesium phosphates as fertilizers in neutral and slightly alkaline soils, Agronomy Journal 101 (2), 323.

Mata-Alvarez, J., Dosta,J., Romero-Güiza, M.S., Fonoll, X., Peces, M., Astals, S. (2014) A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renew Sustain Energy Rev,36,412-427.

Mattiolli, A., Gatti, G.B., Mattuzzi, G.P, Cecchi, F., Bozonella, D. (2017) Co-digestion of the organic fraction of municipal solid waste and sludge improves the energy balance of wastewater treatment plants: Rovereto case study. Renewable Energy 113, 980-988.

Maktabifard, M., Zaborowska, E., Makinia, J. (2018) Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production Rev.Environ. Sci. Bio/Technol. 17, 655-689.

McMathon, K. D., Zheng, D., Stams, A. J. M., Mackie, R. I. and Raskin, L. (2004) Microbial population dynamics during start-up and overload conditions of anaerobic digesters treating municipal solid waste and sewage sludge. Biotechnology and Bioengineering, 87 (7), 823-834.

Meyer C., Preyl V., Steinmetz H., Maier W., Mohn RE., Schönberger H. (2019) The Stuttgart Process (Germany). In: Ohtake H., Tsuneda S. (eds) Phosphorus Recovery and Recycling. Springer, Singapore. https://doi.org/10.1007/978-981-10-8031-9_19.

Mocker, M., Löh, I., Stenzel, F. (2011) Phosporus recivery from sewage sludge, Waste Management, Volume 2, TK Verlag - Fachverlag für Kreislaufwirtschaft, Neuruppin-Nietwerder.

Montag, D. (2008) Phosphorrückgewinnung bei der Abwasserreinigung - Entwicklung eines Verfahrens zur Integration in kommunalen Kläranlagen. Dissertation an der Fakultät für Bauingenieurwesen der Rheinischen-Westfälischen Technischen Hochschule Aachen. 2008. Dissertation (German) http://publications.rwth-aachen.de/record/50037/files/Montag_David.pdf

Nagamani, B and Ramasamy K. (1999) Biogas production technology: An Indian perspective. Current Science 77 (1), 44-55.

Ngheim, D., L., Koch, K., Bozonella, D., Drews, J.E. (2017) Full scale co-digestion of wastewater sludge and food waste: Bottlenecks and possibilities, Renewable and Sustainable Energy Reviews, 72, 354-362.

Nguyen, L., N., Kumar, J., Vu, M., T., Mohammed, J., A., H., Pathak, N., Commault, A., S., Sutherland, D., Zdarta, J., Tyagi, V., K., Nghiem, D., L. (2020) Biomethane production from anaerobic co-digestion at wastewater treatment plants: A critical review on development and innovations in biogas upgrading techniques. Science of The Total Environment. In Press

Nisipeanu, P. (1998) Rechtsfrage der Co-Vergärung in Faultürmen. Tagungsband zur ATV-Bundestagung von 29.09-01.10.1998 (Bremen), ATV-Schriftenreihe Nr 12, 171-187.

OECD (2018), “Energy policy in South East Europe”, in Competitiveness in South East Europe: A Policy Outlook 2018, OECD Publishing, Paris. DOI: https://doi.org/10.1787/9789264298576-17-en

Official Gazette of Republic of Serbia (2009) Waste Management Law No. 36/2009, Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2012) Regulation on limit values of pollutants in surface and ground waters and sediments, and the deadlines for their achievement No. 50/2012, Government of the Republic of Serbia, Belgrade.

Official Gazette of the Republic of Serbia (2019) Regulation on the Establishment of Water Management Program in 2019 No.12/2019.

Official Gazette of Republic of Serbia (2010) Regulation on waste landfilling 92/2010, Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2013) Law on Agriculture and Rural Development *No. 10/2013,* Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2013) Law in Efficient Energy Use, *No. 25/2013,* Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2013) Decree on Incentive measures for electricity generation No 08/2013, Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2013) Decree on Incentive measures for electricity generation No 08/2013, Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2014) Energy law 145/2014, Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2014) Strategy of Agriculture and Rural Development of the Republic of Serbia 2014– 2024, 85/2014, Ministry of Agriculture and the Environment Protection of RS, Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2015). Energy Sector DevelopmentStrategy of the Republic of Serbia for the Period by 2025 with Projections by 2030. Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2016) Regulation on emission limit values in waters and deadlines for the achievement No. 01/2016, Government of the Republic of Serbia, Belgrade.

Official Gazette of Republic of Serbia (2016) Law on Nature Protection 14/2016 (36/2009, 88/2010), Government of the Republic of Serbia, Belgrade

Official Gazette of Republic of Serbia (2017) Water management plan until 2034 03/2017, Government of the Republic of Serbia, Belgrade

Olivier, T., Pouet, M.F. (2006) Sewers, Characterisation and Evolution of Sewage, Wastewater Quality Monitoring and Treatment, 111–118.

Olsson, G. (2015) Water and Energy – Threats and Opportunities, IWA Publishing.

Odum, E., P. (1971) Fundamentals of Ecology, W. B. Saunders Company.

Panepinto, D., Fiorw, S., Zappone, M., Genon, G., Meucci, L. (2016) Evaluation of the energy efficiency of a large wastewater treatment plants in Italy. Applied Energy 161, 404-411.

Pinnekamp, J., Montag, D., Gethke, K., Herbst, H. (2007) Rückgewinnung eines schadstofffreien, mineralischen Kombinationsdüngers Magnesiumammoniumphosphat – MAP aus Abwasser und Klärschlamm. Umwelt Bundes Amt Texte 25/07, Dessau-Roßlau, 2007.

Popp, J., Jahn, M., Matlock, M., Kemper, N. (2012) The Role of Biotechnology in a Sustainable Food Supply, Cambridge University Press.

Piersson, T. (2018) The Stuttgart Process. In: Phosphorus: Polluter and Resource of the Future: Removal and Recovery from Wastewater, IWA Publishing.

Rakijaš, M. (2012) New Regulation of Waste Disposal and the Current State in Serbia. Paper for the International Conference-Waste Waters, Municipal Solid Wastes and Hazardous Wastes. Belgrad,175-181.

Ren, N., Wang, B. and Huang, J. H. (1997) Ethanol-type fermentation from carbohydrate in high rate acidogenic reactor. Biotechnology and Bioengineering, 54, (5), 428-433.

Ringler, C., Bhaduri, A., Lawford, R. (2013) The nexus across water, energy, land and food (WELF): potentials for improved resources use efficiency? Current Opinion Environmental Sustainability 5 (6), 617-624.

Rosenwinkel, K.-H., Kroiss, H., Dichtl, N., Seyfried, C.-F., Weiland, P. (Hrsg.) (2015) Anaerobtechnik - Abwasser-, Schlamm- und Reststoffbehandlung, Biogasgewinnung, Springer.

Rosmarin, A. (2004) The Precarious Geopolitics of Phosphorous Down to Earth. Science and Environment Fortnightly, 27–31.

Römer, W. (2006) Plant availability from recycling products and phosphate fertilizer in a growth-chamber trial with rye seedlings, Journal of Plant Nutrition and Soil Science 169 (6), 826-832.

Sauvé S., Bernard S., Sloan P. (2016) Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environmental Development 17, 48–56.

Schmidt, J. E., Mladenovska, Z., Lange, M. and Ahring, B. K. (2000). Acetate conversion in anaerobic biogas reactors: Traditional and molecular tools for studying this important group of anaerobic microorganisms. *Biodegradation*, 11, 359-364.

Schneider, D. (2011) Hybrid Nature: Sewage Treatment and the Contradictions of the Industrial Ecosystem. Cambridge: The MIT Press.

Schopf, K., Judex, J., Schmi, B., Kienberger, T. (2018) Modelling the bioenergy potential of municipal wastewater treatment plants Water Sci. Technol. 77 (11), 2613–23.

Sedlak, D. (2014). Water 4.0: The Past, Present, and Future of the World’s Most Vital Resource. New Haven, NJ: Yale University Press.

SEPA (2014) Stanje zivotne sredine u Repubici Srbiji – kratak pregled. Available at: http://www.sepa.gov.rs/download/SEPA_ECOEXPO_2015.pdf

SEPA (2019) The report on waste management for the period from 2011 to 2018.

Shen,Y., Linville, J.L., Urgun-Demirtas, M., Mintz, M.M., Snyder, S.W. (2015) An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs, Renewable and Sustainable Energy Reviews 50 (2015) 346–362.

Solomou, N., Stamatoglou, A., Malamis, M., Katsou, E., Costa, C. N., Loizidou, M. (2014) An integrated solution to wastewater and biodegradable organic waste management by applying anaerobic digestion and membrane bioreactor processes. Water Practice and Technology, 9 (4): 464–474.

SORSa. (2013a) Agriculture and Fishery. The Statistical Office of the Republic of Serbia, Belgrade.

SORSb. (2013b) Census of Agriculture 2012 in the Republic of Serbia. The Statistical Office of the Republic of Serbia, Belgrade.

SORS (2014) Eco- Bulletin 2013. The Statistical Office of the Republic of Serbia, Belgrade.

SORS (2016) Statistical Yearbook 2016, The Statistical Office of the Republic of Serbia, Belgrade.

SORS (2019) Eco-Bulletin 628. The Statistical Office of the Republic of Serbia, Belgrade.

SEPA (2014) Izvestaj o stanju zivotne sredine u Republici Srbiji, SEPA; Belgrade. Available at: http://www.sepa.gov.rs/download/Izvestaj2014.pdf

SEPA (2015) *Status povrsinskih voda Srbije*, SEPA, Belgrade. Avilable at: http://www.sepa.gov.rs/download/VodeSrbije/StatusPovrsinskihVodaSrbije.pdf

Stanisavljevic, N., Vujovic, S., Zivancev, M., Batinic, B., Tot, B., Ubavin, F. (2015) Application of MFA as a decision support tool for waste management in small municipalities—case study of Serbia. Waste Manag. Res., 33 (6), pp. 550-560 doi.org/10.1177/0734242X15587735

Strippel, V.F (2016) Aktueller Stand der Abfallvergärung in Deutschland, Biogas J, 2 (2016), 45-47.

Thomas O., Pouet MF. (2004) Wastewater Quality Monitoring: On-Line/On-Site Measurement. In: Barceló D. (eds) Water Pollution. The Handbook of Environmental Chemistry, vol 2. Springer, Berlin, Heidelberg. https://doi.org/10.1007/b98617

Tonini, D., Saveyn, H. G. M. & Huygens, D. (2019) Environmental and health co-benefits for advanced phosphorus recovery Nat. Sustain. https:// doi.org/10.1038/s41893-019-0416-x.

Tesic, M., Kiss, F., Zavargo, Z. (2011) Renewable energy policy in the Republic of Serbia; Renew Sustain Energy Rev, 15, 752–758.

UBA (2018) Sewage Sludge Disposal in the Federal Republic of Germany. Available at: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/190116_uba_fb_klaerschlamm_engl_bf.pdf

UN (2014) Report of the Open Working Group of the General Assembly on Sustainable Development Goals. Available at: http://undocs.org/A/68/970

UN (2019) World Population Prospects. Department of Economic and Social Affairs, Population Division. https://population.un.org/wpp/

UNDP (2018) Position paper: Status of using agricultural biomass for energy purposes in Serbia.

UNEP (2011) Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel. Available at: http://www.gci.org.uk/Documents/Decoupling_Report_English.pdf

UNEP (2013) Green economy and trade: trends, challenges and opportunities. United Nations Environment Programme, Nairobi, Kenya.

USAID. 2017. Climate Risk Profile: Serbia. https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID_Climate%20Change%20Risk%20Profile_Serbia.pdf

hange%20Risk%20Profile_Serbia.pdf

U.S. Geological Survey (2019) Mineral commodity summaries 2019: U.S. Geological Survey, 200 p., Available at: https://doi.org/10.3133/70202434.

UNESCO (2117) Wastewater: the Untrepped Resources. The United Nations World Water Development Report 2017. Available at: http://www.unesco.org/new/typo3temp/pics/0d623deb50.jpg

Vaneeckhaute, C., Lebuf, V., Michaels, E., Belia, E., Vanrollegham, P. A., Tack, M. F., Meers, E. (2017) Nutrient Recovery from Digestate: Systematic Technology Review and Product Classification, Waste Biomass Valor.8,21–40.

Van der Hoek, J.P, de Fooij, H., Ouderkerkerdijk, K. (2016) Wastewater as a resource: Strategies to recover resources from Amsterdam’s wastewater, Resource, Conservation and Recycling, 113, 53-64.

Van Loosdrecht, M.C.L., Brdjanovic, D. (2014) Anticipating the next century of wastewater treatment, Science, 344, 1452 - 1453.

Van Vuuren, D. P., Bouwman, A. F., and Beusen, A. H. W. (2010) Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion, Global Environ. Chang., 20, 428–439, https://doi.org/10.1016/j.gloenvcha.2010.04.004.

Venghaus, S., Hake, J.F. (2018). Nexus thinking in current EU policies – The interdependence among food, energy and water resources. Environmental Sciences and Policy.

Venkatesh, G., Chan, A., Brattebø, H. (2014) Understanding the water-energy-carbon nexus in urban water utilities: comparison of four city case studies and the relevant influencing factors. Energy 75, 153–66.

Volk, T., Erjavec, E., Mortensen, K. (2014): Agricultural Policy and European Integration in South-eastern Europe, FAO, Budapest, 153–169.

Vujić, G., & Tot, B. (2020). Solid Waste Management in the Republic of Serbia. In Pariatamby, A., Shahul Hamid, F., & Bhatti, M. S. (Ed.), Sustainable Waste Management Challenges in Developing Countries (pp. 306-326). IGI Global. http://doi:10.4018/978-1-7998-0198-6.ch013

Vujic, G., Vujoviavljevic, N., Batinic, B., Jurakic, Z., Ubavin, D. (2015) Barriers for implementation of “waste to energy” in developing and transition countries: a case study of Serbia, Journal of Material Cycles and Waste Management, 19 (1).

Vujovic, S., Stanisavljevic, N., Fellner, J., Tosic, N., Lederer, J. (2020) Biodegradable waste management in Serbia and its implication on P flows, Resources, Conservation and Recycling, Volume 161, doi.org/10.1016/j.resconrec.2020.104978

Wiechmann, B., Dienemann, C., Kabbe, C., Brandt, S., Vogel, I., Roskosch, A. (2013) Klärschlammentsorgung in der Bundesrepublik Deutschland Umweltbundesamt, Bonn.

Wilkie, A. (2005) Anaerobic Digestion: Biology and Benefits. Dairy Manure Management: Treatment, Handling and Community Relations. NRAES-176, 63-67.

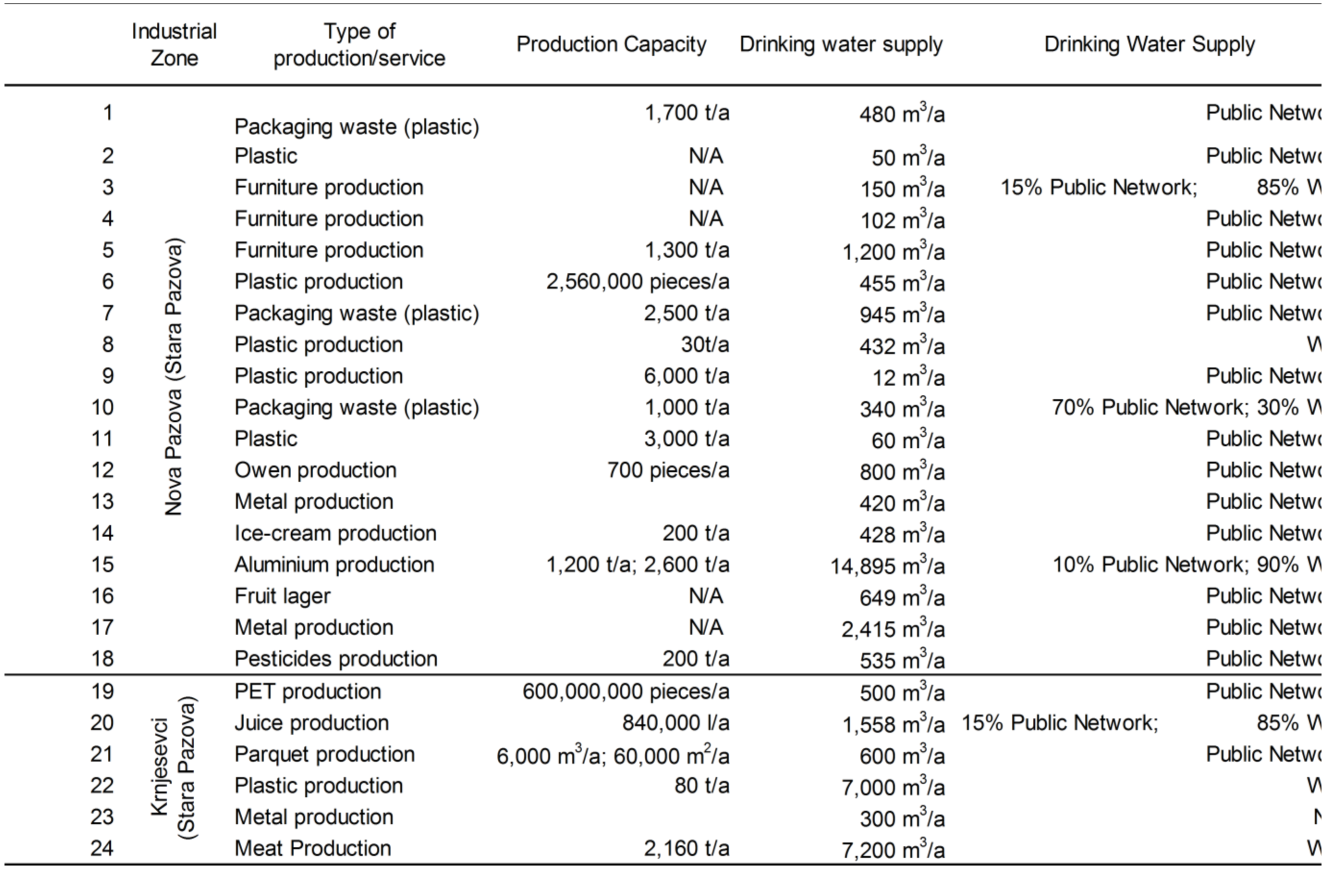
World Bank (2015) Water and Wastewater Services in the Danube Region: Serbia Country Note. Washington, DC. https://openknowledge.worldbank.org/handle/10986/22136

World Bank Open Data (2020) https://data.worldbank.org/ Web. 01.Dec.2020

Zupancic, G.D., Uranjek-Ževart, N., Roš, M. (2008) Full-scale anaerobic co-digestion of organic waste and municipal sludge. Biomass Bioenergy 32 (2), 162–16

Appendix

Appendix 1 - Results of the Industrial wastewater survey (Complition Status: September 2014)



	Industrial Zone	Type of production/service	Production Capacity	Drinking water supply	Drinking Water Supply
1	Nova Pazova (Stara Pazova)	Packaging waste (plastic)	1,700 t/a	480 m^3/a	Public Netw
2		Plastic	N/A	50 m^3/a	Public Netw
3		Furniture production	N/A	150 m^3/a	15% Public Network; 85% W
4		Furniture production	N/A	102 m^3/a	Public Netw
5		Furniture production	1,300 t/a	1,200 m^3/a	Public Netw
6		Plastic production	2,560,000 pieces/a	455 m^3/a	Public Netw
7		Packaging waste (plastic)	2,500 t/a	945 m^3/a	Public Netw
8		Plastic production	30t/a	432 m^3/a	W
9		Plastic production	6,000 t/a	12 m^3/a	Public Netw
10		Packaging waste (plastic)	1,000 t/a	340 m^3/a	70% Public Network; 30% W
11		Plastic	3,000 t/a	60 m^3/a	Public Netw
12		Owen production	700 pieces/a	800 m^3/a	Public Netw
13		Metal production		420 m^3/a	Public Netw
14		Ice-cream production	200 t/a	428 m^3/a	Public Netw
15		Aluminium production	1,200 t/a; 2,600 t/a	14,895 m^3/a	10% Public Network; 90% W
16		Fruit lager	N/A	649 m^3/a	Public Netw
17		Metal production	N/A	2,415 m^3/a	Public Netw
18		Pesticides production	200 t/a	535 m^3/a	Public Netw
19	Krnjesevci (Stara Pazova)	PET production	600,000,000 pieces/a	500 m^3/a	Public Netw
20		Juice production	840,000 l/a	1,558 m^3/a	15% Public Network; 85% W
21		Parquet production	6,000 m^3/a; 60,000 m^2/a	600 m^3/a	Public Netw
22		Plastic production	80 t/a	7,000 m^3/a	W
23		Metal production		300 m^3/a	N
24		Meat Production	2,160 t/a	7,200 m^3/a	W

Appendix 1 - Results of the Industrial wastewater survey (Complition Status: September 2014)

	Industrial Zone	Type of production/service	Production Capacity	Drinking water supply	Drinking Water Supply	Wastewa producti
25	Stara Pazova	Meat Production	N/A	N/A	N/A	8.000 m
26		Meat Production	12 t/a	N/A	N/A	1.200 m
27		Meat Production	400 t/a	4,200 m^3/a	Public Network	4.200 m
28		Milk production	1,800,000 l/a	720 m^3/a	Public Network	720 m
29		Ice-cream production	22,500 t/a	70,000 m^3/a	Well	53.000 m
30		Aluminium production	3,300 t/a	2,112 m^3/a	Public Network	2.112 m
31		Plastic production	120 pieces/a	25 m^3/a	Public Network	25 m
32		Construction material	N/A	600 m^3/a	Public Network	600 m
33		Beton	3,000 m^3/a	100 m^3/a	Well	100 m
34		Sponge production	680 t/a	140 m^3/a	Public Network	140 m
35		Spices production	15,000 t/a	600 m^3/a	Public Network	600 m
36		Logistic Centre	N/A	260 m^3/a	Public Network	260 m
37		Grain mill products	32,000 t/a	810 m^3/a	Public Network	810 m
38		Furniture production	N/A	10 m^3/a	Public Network	10 m
39		Metal production	1,000 t/a	2 m^3/a	Public Network	2 m
40		Electrical installations	N/A	9,500 m^3/a	Public Network	9,500 m
41		Steal production	N/A	300 m^3/a	Public Network	300 m
42	Banovci	Milk production	180,000 l/a	100 m^3/a	Public Network	100 m
43		Milk production	3,900,000 l/a	648 m^3/a	Public Network	648 m
44		Meat Production	780,000 pieces/a	11,000 m^3/a	80% Public Network; 20% Well	11,000 m

	Industrial Zone	Type of production/service	Production Capacity	Drinking water supply	Drinking Water Supply	Wastewater production
45	Indjija	Beverages production				97,395 m^3/a
46		Food industry				35,959 m^3/a
47		Meat industry				19,580 m^3/a
48		Artificial food for pats				14,898 m^3/a
49		Commercial objects				14,008 m^3/a
50		Food industry				11,061 m^3/a
51		Food industry				10,386 m^3/a
52		Medicine				10,145 m^3/a
53		Pumps production				5,273 m^3/a
54		Commercial object				5,066 m^3/a
55		Commercial object				4,863 m^3/a
56		Milk production				4,131 m^3/a
57		Fish trade				3,413 m^3/a
58		Commercial object				3,323 m^3/a
59		Commercial object				2,766 m^3/a
60		Meat trade				2,328 m^3/a
61		Batteries recycling				2,204 m^3/a
62		Chemical industry				1,650 m^3/a
63		Metal production				1,503 m^3/a
64		Meat production				1,445 m^3/a
65		Commercial object				1,328 m^3/a
66		Automotive electronic parts				838 m^3/a
67		Gas and energy equipment				831 m^3/a
68		Metal production				693 m^3/a
69		Packaging waste (plastic)				557 m^3/a
70		Packaging waste (plastic)				N/A
72		Tabaco industry				N/A
73		Metal production				N/A
74		Paper production				N/A
75		Pigs breading				N/A
76		Plastic production				N/A

Appendix 2 - Bio-waste Survey

WASTE MANAGEMENT

Explanation about the questionary

This questionary is a part of doctoral research of Ms. Jovana Husemann.

Responsible person:

Dipl.-Biol. Jovana Husemann, M.Sc., M.Eng.

University Stuttgart
ISWA - Institute for Sanitary Engineering, Water Quality and Solid Waste Management

Wastewater Technology Department

Bandtäle 2
70569 Stuttgart
Germany
Tel.: +49 711 685 - 63949
Fax.: +49 711 685 - 63729

jovana.husemann@iswa.uni-stuttgart.de

	year	**For period 2003-2012**											
	month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number of inhabitants													
Number of inhabitants with waste collection													
Municipal waste quantity	t/month												
Percentage of organic waste	%												
Grass from public surfaces	t/month												
The rest of green cut from public surfaces	t/month												
Bio-waste from markets	t/month												

Appendix 3 - Agro-Survey

AGRICULTURE

Explanation about the questionary

This questionary is a part of doctoral research of Ms. Jovana Husemann.
This questionary consists of two parts: "crop husbandry" and "animal husbandry". Thank you for participating

Responsiblle person:

Dipl.-Biol. Jovana Husemann, M.Sc., M.Eng.

University Stuttgart
ISWA - Institude for Sanitary Engineering, Water Quality and Solid Waste Management

Wastewater Technology Department

Bandtäle 2
70569 Stuttgart
Germany

Tel.: +49 711 685 - 63949
Fax.: +49 711 685 - 63729

jovana.husemann@iswa.uni-stuttgart.de

Name of Agricultural Unit	
Contact Person	
Contact	

1. Crop husbandry

	For period 2003-2012				
	Surface	Yield per ha	Corn crop ratio	Seasonal availability per year (from which to which month)	
	ha	t/ha	%		
Corn					
Whole cereal					
Barley					
Grass					
Sugar beet					
Raps seeds					
Sunflower					
Rest (plase specify)					

	% of straw remains on fields	% of straw used for animal bedding	% of straw which is used for balling	% of biomass which is not used, and it is considered as a waste product	
Corn					
Whole cereal					
Barley					
Grass					
Sugar beet					
Raps seeds					
Sunflower					
Rest (plase specify)					

2. Animal husbandry

		Average days in stable per year	Type - slurry / Manure	% of slurry which is waste product	Slurry/Mist management	Average animal weight	% of slurry which is waste product	Average number of animals per year									
								2012	2011	2010	2009	2008	2007	2006	2005	2004	2003
		day/annum		%		kg	%										
Pigs	Piglets																
	Fattened																
	Sows																
Cattle	Calves																
	Heifers																
	Pregnant heifers																
	Breeding cows																
	Bulls																
Sheep																	
Goat																	
Horses																	
Poultry	chicken																
	geese																
	ducks																
Rest																	

Appendix 4 - Values used for mass balance

Substrate	% DM	% oDM from DM	Specific biogas production m^3/t FW	Specific methane production m^3/t oDM
Corn silage	33	95	200	340
Whole cereal silage	33	95	190	329
Green rye silage	25	90	150	324
Grass silage	35	90	180	310
Sugar beet silage	23	90	130	350
Rapeseed silage	16	90	90	350
Sunflower silage	25	90	120	298
Cow manure	10	80	25	210
Cow liquid manure	25	80	80	250
Pig manure	6	80	28	250
Poultry manure	40	75	140	280
Horses excrements	28	75	63	165
Green cut	12	87,5	175	369
Bio household waste	40	50	123	74
Brewer's grains	23	75	118	313
Cereal distillers	6	94	39	385
Potato stillage	6	85	34	362
Fruit distillers	2,5	95	15	285
Raw glycerine	N/A	N/A	250	147
Rapeseed press cake	92	87	660	396
Potato pulp	13	90	80	336
Z-press cutlets	24	95	68	218
Molasses	85	88	315	308
Apple pomace	35	88	148	453
Milk	13	95	148	475
Whey	5	85	148	450

Based on FRN,2016 and Rosenwinkel et al, 2015.

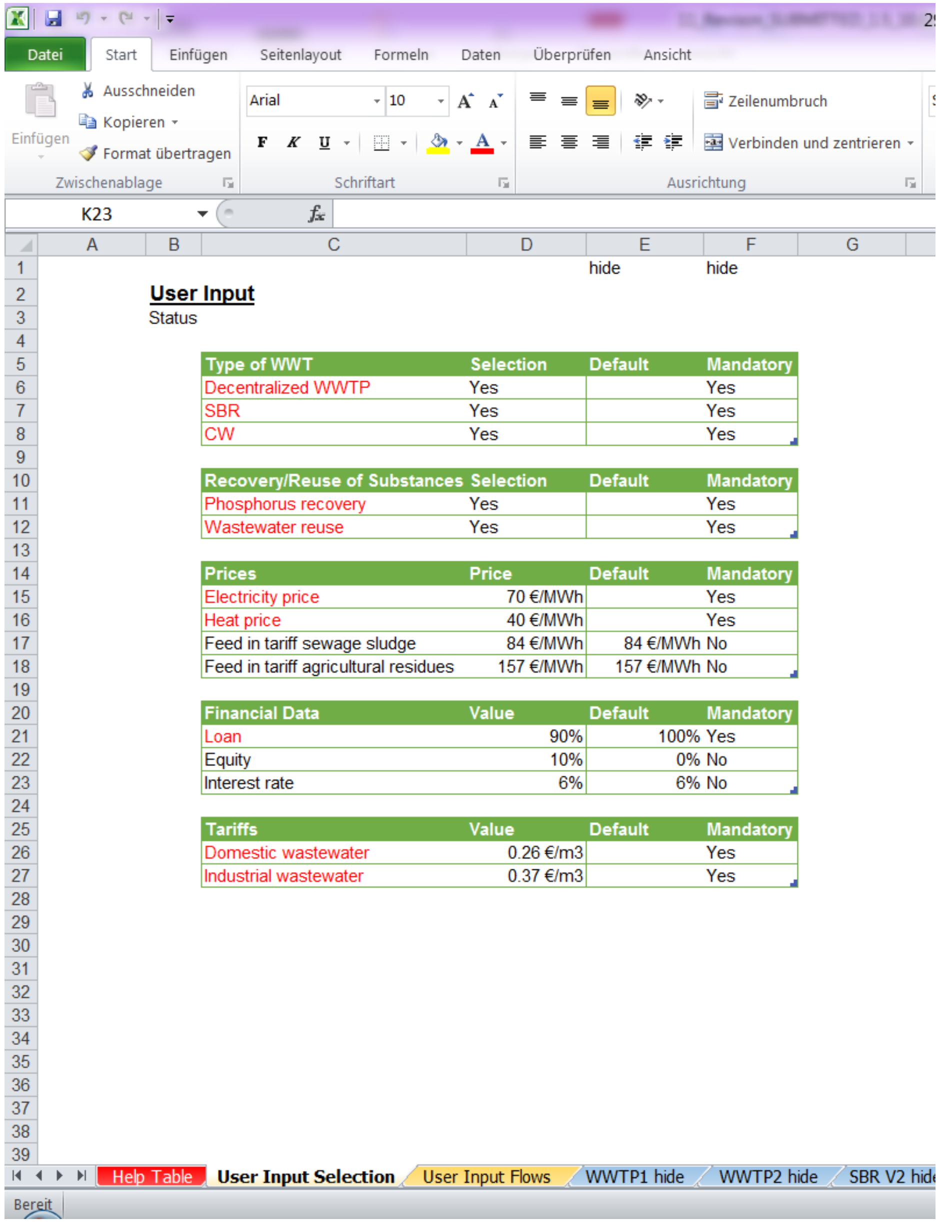
Appendix 5 - Parameters used for the financial analysis

Paremeter	Value	Reference
BOD,limit values	20 mg/l	Official Gazette of RS,1/2016
COD,limit values	90 mg/l	Official Gazette of RS, 1/2016
P,limit values	1 mg/l	Official Gazette of RS, 1/2016
N,limit values	10 mg/l	Official Gazette of RS, 1/2016
Pre-treatment duration	0.5-1 h	Assumption
Design wastewater temperature	12 º C	Assumption
Sludge age	11 days	Assumption
Primary sludge DM content	3.00 %	DWA, 2006b
Primary sludge DM content after mechanical thickening	7.00 %	DWA, 2006b
Secondary sludge DM content	0.73 %	DWA, 2006b
Secondary sludge DM content after static thickening	6.00 %	DWA, 2006
Anaerobic Digester Retention time	20 days	Assumption
CHP efficiency electrical energy	40%	FNR, 2013
CHP efficiency thermal energy	45%	FNR, 2014
Energy content biomass	6 kWh/m^3	DWA-M 363
Energy content livestock	6.25 kWh/m^3	DWA-M 363
Energy content organic waste	5.75 kWh/m^3	DWA-M 363
Energy content industrial waste	5.75 kWh/m^3	DWA-M 363
Energy content sewage sludge	6.5 kWh/m^3	DWA-M 363
Specific energy demand for wastewater treatment	30 kWh/(PE*a)	DWA, 2013
Specific energy demand for sewage sludge dewatering	0.3 kWh/(PE*a)	DWA, 2013
WWTP, SBR Specific energy demand disinfection	30 Wh/m^3	DWA, 2013
CW Specific energy demand disinfection	10 Wh/m^3	DWA, 2013

Type of Costs	Value	Reference
Specific costs construction WWTP	125 €/P.E	Gauff Ingenieure et al.a, 2012; Haskoning Nederland B.V. Water et al., 2007
Specific costs SBR	425 €/P.E	Horstmeyer et al., 2014
Specific costs Constructed Wetland	320 €/P.E	Horstmeyer et al., 2014
Specific costs Digester 1	2,000 €/kW	IWR, 2017
Specific costs Digester 2	4,000 €/kWel	FNR, 2013
Specific costs MAP recovery	5.4 €/P.E	Egle et al., 2016

Specific costs disinfection WWTP	7 €/P.E	DWA, 2013
Specific costs disinfection SBR	52 €/P.E	DWA, 2013
Specific costs disinfection Construed Wetland	52 €/P.E	DWA, 2013
Specific annual costs labour	14,400 €/a	Interview
Specific costs electricity	USER defined	
Specific annual heat	USER defined	
Specific operation costs MAP production	5.7 €/P.E*a	Egle et al., 2016
Transport	0.14 €/km	Egle et al., 2016
Expected maximal distance of transport	20 km	Bertanza et al., 2016
Costs of disposals (agricultural application)	40 €/t DM	Bertanza et al., 2016
Costs of disposals (landfill)	60 €/t DM	Bertanza et al., 2018
Specific chemical demand P precipitation	2,7 kgFeCl$_3$/kgP	
Specific price per chemical	0.9 €/kgFeCl$_3$	
Specific revenues electricity	USER defined	
Specific revenues thermal energy	35 €/MWh	estimation
Specific revenues MAP	350 €/t	estimation
Specific costs fertilizer	10 €/t	estimation
Annual maintenance - out of investment costs	2%	Egle et al., 2016, estimation
Depreciation	20 years	Bertanza et al., 2018

Appendix 6 – DST, example of the Scenario d-4



hide hide

User Input

Status

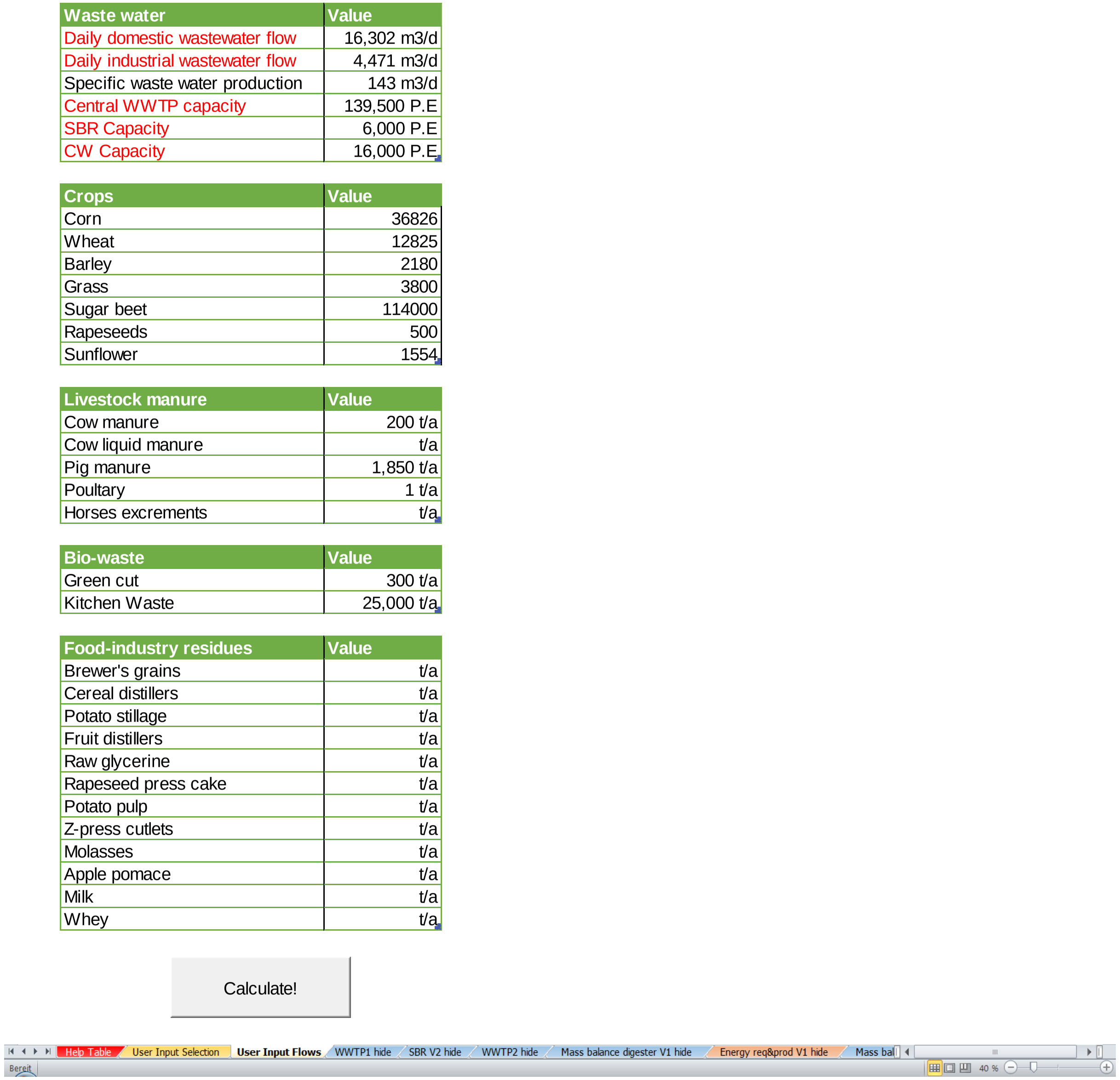
Type of WWT	Selection	Default	Mandatory
Decentralized WWTP	Yes		Yes
SBR	Yes		Yes
CW	Yes		Yes

Recovery/Reuse of Substances	Selection	Default	Mandatory
Phosphorus recovery	Yes		Yes
Wastewater reuse	Yes		Yes

Prices	Price	Default	Mandatory
Electricity price	70 €/MWh		Yes
Heat price	40 €/MWh		Yes
Feed in tariff sewage sludge	84 €/MWh	84 €/MWh	No
Feed in tariff agricultural residues	157 €/MWh	157 €/MWh	No

Financial Data	Value	Default	Mandatory
Loan	90%	100%	Yes
Equity	10%	0%	No
Interest rate	6%	6%	No

Tariffs	Value	Default	Mandatory
Domestic wastewater	0.26 €/m3		Yes
Industrial wastewater	0.37 €/m3		Yes



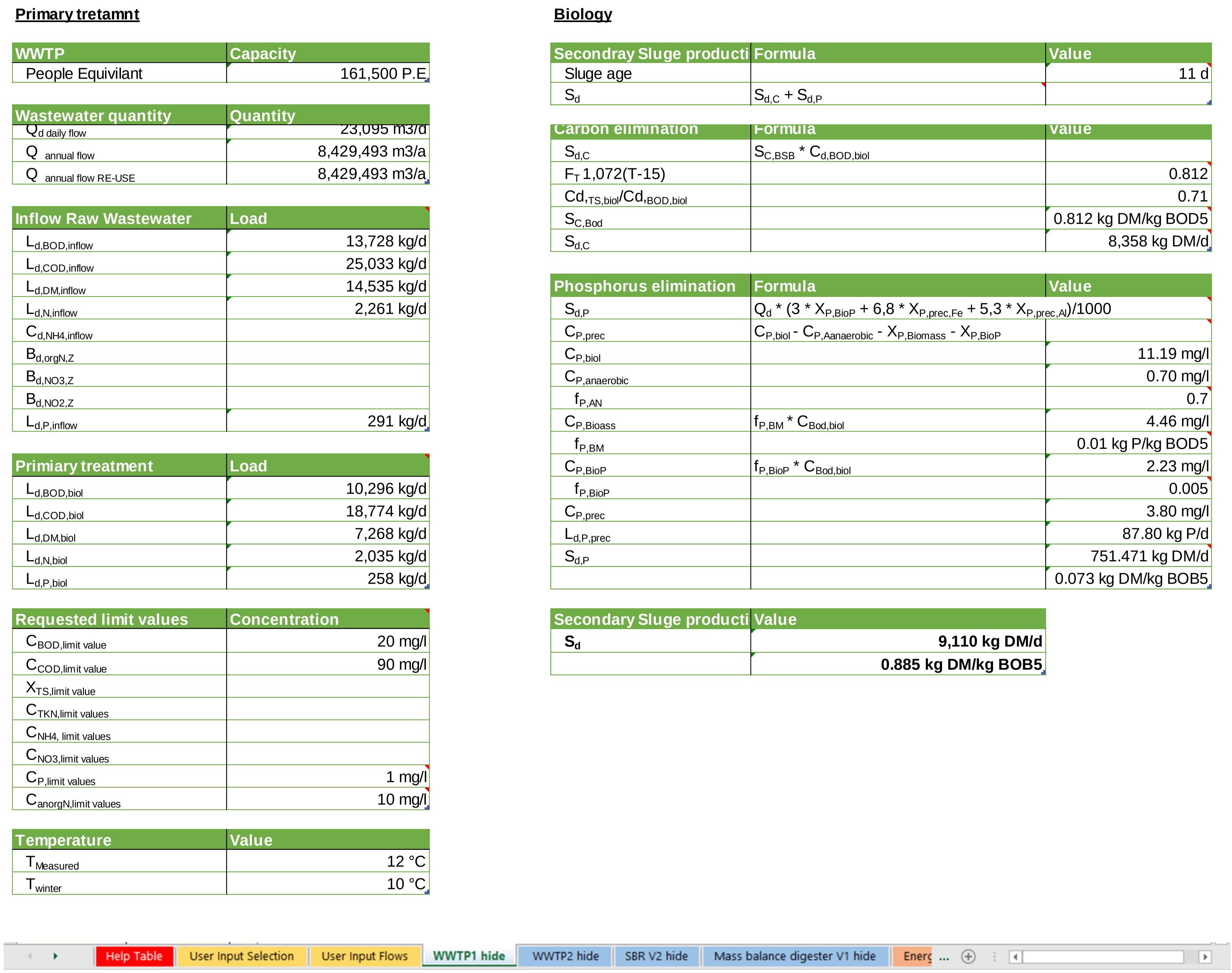
Waste water	Value
Daily domestic wastewater flow	16,302 m3/d
Daily industrial wastewater flow	4,471 m3/d
Specific waste water production	143 m3/d
Central WWTP capacity	139,500 P.E
SBR Capacity	6,000 P.E
CW Capacity	16,000 P.E

Crops	Value
Corn	36826
Wheat	12825
Barley	2180
Grass	3800
Sugar beet	114000
Rapeseeds	500
Sunflower	1554

Livestock manure	Value
Cow manure	200 t/a
Cow liquid manure	t/a
Pig manure	1,850 t/a
Poultary	1 t/a
Horses excrements	t/a

Bio-waste	Value
Green cut	300 t/a
Kitchen Waste	25,000 t/a

Food-industry residues	Value
Brewer's grains	t/a
Cereal distillers	t/a
Potato stillage	t/a
Fruit distillers	t/a
Raw glycerine	t/a
Rapeseed press cake	t/a
Potato pulp	t/a
Z-press cutlets	t/a
Molasses	t/a
Apple pomace	t/a
Milk	t/a
Whey	t/a



Primary tretamnt

WWTP	Capacity
People Equivilant	161,500 P.E

Wastewater quantity	Quantity
$Q_{d\ daily\ flow}$	23,095 m3/d
$Q_{annual\ flow}$	8,429,493 m3/a
$Q_{annual\ flow\ RE-USE}$	8,429,493 m3/a

Inflow Raw Wastewater	Load
$L_{d,BOD,inflow}$	13,728 kg/d
$L_{d,COD,inflow}$	25,033 kg/d
$L_{d,DM,inflow}$	14,535 kg/d
$L_{d,N,inflow}$	2,261 kg/d
$C_{d,NH4,inflow}$	
$B_{d,orgN,Z}$	
$B_{d,NO3,Z}$	
$B_{d,NO2,Z}$	
$L_{d,P,inflow}$	291 kg/d

Primiary treatment	Load
$L_{d,BOD,biol}$	10,296 kg/d
$L_{d,COD,biol}$	18,774 kg/d
$L_{d,DM,biol}$	7,268 kg/d
$L_{d,N,biol}$	2,035 kg/d
$L_{d,P,biol}$	258 kg/d

Requested limit values	Concentration
$C_{BOD,limit\ value}$	20 mg/l
$C_{COD,limit\ value}$	90 mg/l
$X_{TS,limit\ value}$	
$C_{TKN,limit\ values}$	
$C_{NH4,\ limit\ values}$	
$C_{NO3,limit\ values}$	
$C_{P,limit\ values}$	1 mg/l
$C_{anorgN,limit\ values}$	10 mg/l

Temperature	Value
$T_{Measured}$	12 °C
T_{winter}	10 °C

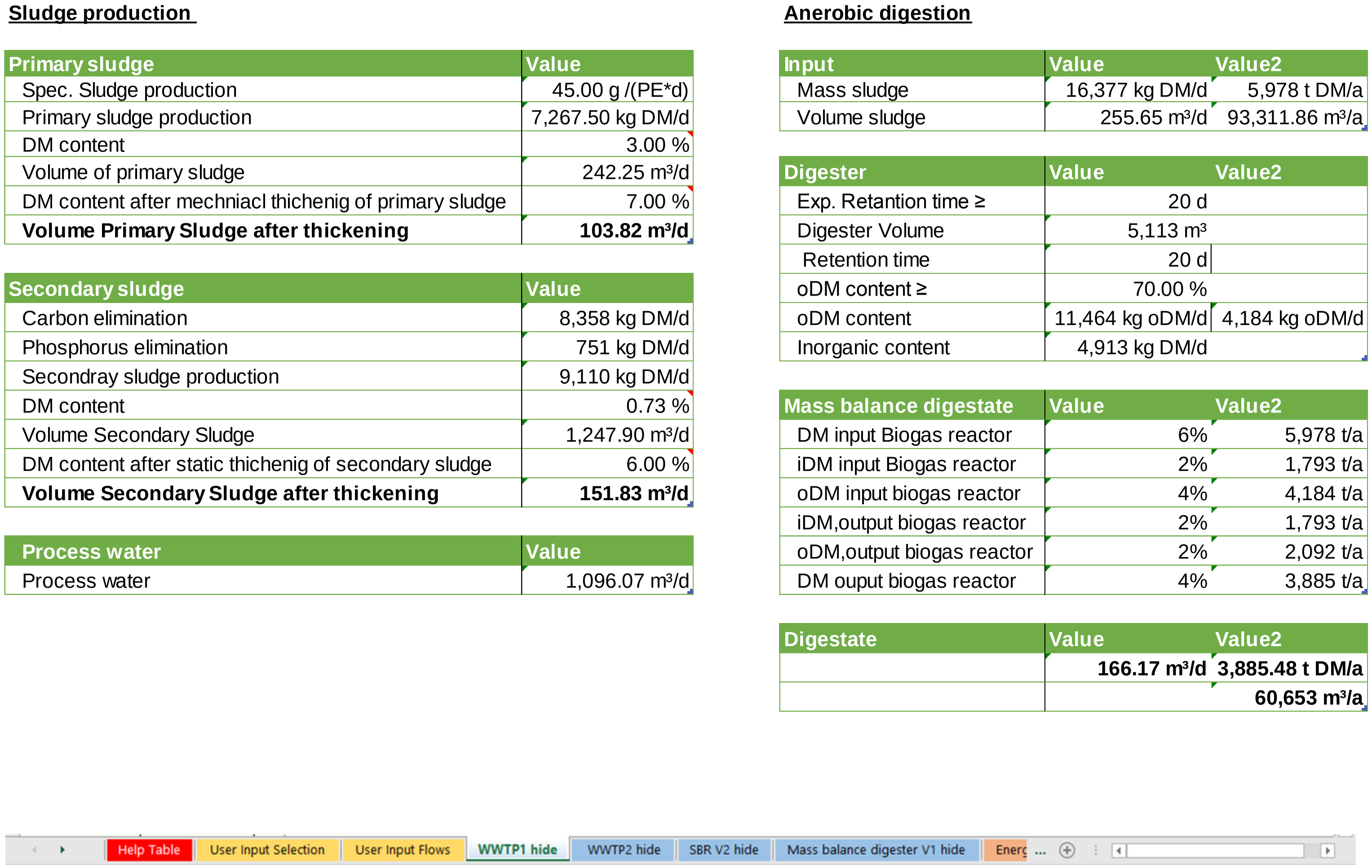
Biology

Secondray Sluge producti	Formula	Value
Sluge age		11 d
S_d	$S_{d,C} + S_{d,P}$	

Carbon elimination	Formula	Value
$S_{d,C}$	$S_{C,BSB} * C_{d,BOD,biol}$	
F_T 1,072(T-15)		0.812
$Cd,_{TS,biol}/Cd,_{BOD,biol}$		0.71
$S_{C,Bod}$		0.812 kg DM/kg BOD5
$S_{d,C}$		8,358 kg DM/d

Phosphorus elimination	Formula	Value
$S_{d,P}$	$Q_d * (3 * X_{P,BioP} + 6,8 * X_{P,prec,Fe} + 5,3 * X_{P,prec,Al})/1000$	
$C_{P,prec}$	$C_{P,biol} - C_{P,Aanaerobic} - X_{P,Biomass} - X_{P,BioP}$	
$C_{P,biol}$		11.19 mg/l
$C_{P,anaerobic}$		0.70 mg/l
$f_{P,AN}$		0.7
$C_{P,Bioass}$	$f_{P,BM} * C_{Bod,biol}$	4.46 mg/l
$f_{P,BM}$		0.01 kg P/kg BOD5
$C_{P,BioP}$	$f_{P,BioP} * C_{Bod,biol}$	2.23 mg/l
$f_{P,BioP}$		0.005
$C_{P,prec}$		3.80 mg/l
$L_{d,P,prec}$		87.80 kg P/d
$S_{d,P}$		751.471 kg DM/d
		0.073 kg DM/kg BOB5

Secondary Sluge producti	Value
S_d	**9,110 kg DM/d**
	0.885 kg DM/kg BOB5



Sludge production

Primary sludge	Value
Spec. Sludge production	45.00 g /(PE*d)
Primary sludge production	7,267.50 kg DM/d
DM content	3.00 %
Volume of primary sludge	242.25 m³/d
DM content after mechniacl thichenig of primary sludge	7.00 %
Volume Primary Sludge after thickening	**103.82 m³/d**

Secondary sludge	Value
Carbon elimination	8,358 kg DM/d
Phosphorus elimination	751 kg DM/d
Secondray sludge production	9,110 kg DM/d
DM content	0.73 %
Volume Secondary Sludge	1,247.90 m³/d
DM content after static thichenig of secondary sludge	6.00 %
Volume Secondary Sludge after thickening	**151.83 m³/d**

Process water	Value
Process water	1,096.07 m³/d

Anerobic digestion

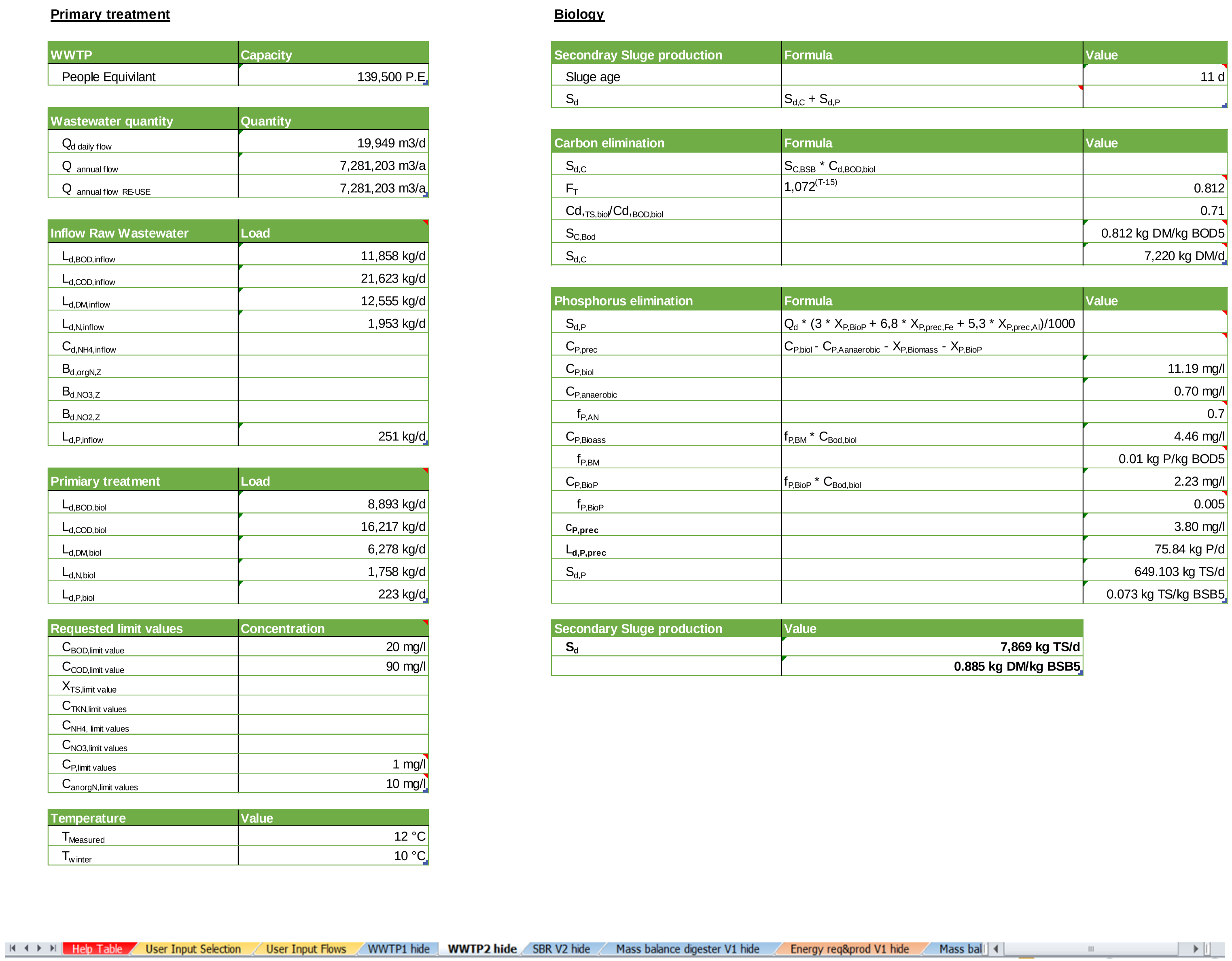
Input	Value	Value2
Mass sludge	16,377 kg DM/d	5,978 t DM/a
Volume sludge	255.65 m³/d	93,311.86 m³/a

Digester	Value	Value2
Exp. Retantion time ≥	20 d	
Digester Volume	5,113 m³	
Retention time	20 d	
oDM content ≥	70.00 %	
oDM content	11,464 kg oDM/d	4,184 kg oDM/d
Inorganic content	4,913 kg DM/d	

Mass balance digestate	Value	Value2
DM input Biogas reactor	6%	5,978 t/a
iDM input Biogas reactor	2%	1,793 t/a
oDM input biogas reactor	4%	4,184 t/a
iDM,output biogas reactor	2%	1,793 t/a
oDM,output biogas reactor	2%	2,092 t/a
DM ouput biogas reactor	4%	3,885 t/a

Digestate	Value	Value2
	166.17 m³/d	**3,885.48 t DM/a**
		60,653 m³/a

***Appendix 6 – DST**, example of the Scenario d-4*



Primary treatment

WWTP	Capacity
People Equivilant	139,500 P.E

Wastewater quantity	Quantity
$Q_{d\ daily\ flow}$	19,949 m3/d
$Q_{\ annual\ flow}$	7,281,203 m3/a
$Q_{\ annual\ flow\ RE\text{-}USE}$	7,281,203 m3/a

Inflow Raw Wastewater	Load
$L_{d,BOD,inflow}$	11,858 kg/d
$L_{d,COD,inflow}$	21,623 kg/d
$L_{d,DM,inflow}$	12,555 kg/d
$L_{d,N,inflow}$	1,953 kg/d
$C_{d,NH4,inflow}$	
$B_{d,orgN,Z}$	
$B_{d,NO3,Z}$	
$B_{d,NO2,Z}$	
$L_{d,P,inflow}$	251 kg/d

Primiary treatment	Load
$L_{d,BOD,biol}$	8,893 kg/d
$L_{d,COD,biol}$	16,217 kg/d
$L_{d,DM,biol}$	6,278 kg/d
$L_{d,N,biol}$	1,758 kg/d
$L_{d,P,biol}$	223 kg/d

Requested limit values	Concentration
$C_{BOD,limit\ value}$	20 mg/l
$C_{COD,limit\ value}$	90 mg/l
$X_{TS,limit\ value}$	
$C_{TKN,limit\ values}$	
$C_{NH4,\ limit\ values}$	
$C_{NO3,limit\ values}$	
$C_{P,limit\ values}$	1 mg/l
$C_{anorgN,limit\ values}$	10 mg/l

Temperature	Value
$T_{Measured}$	12 °C
T_{winter}	10 °C

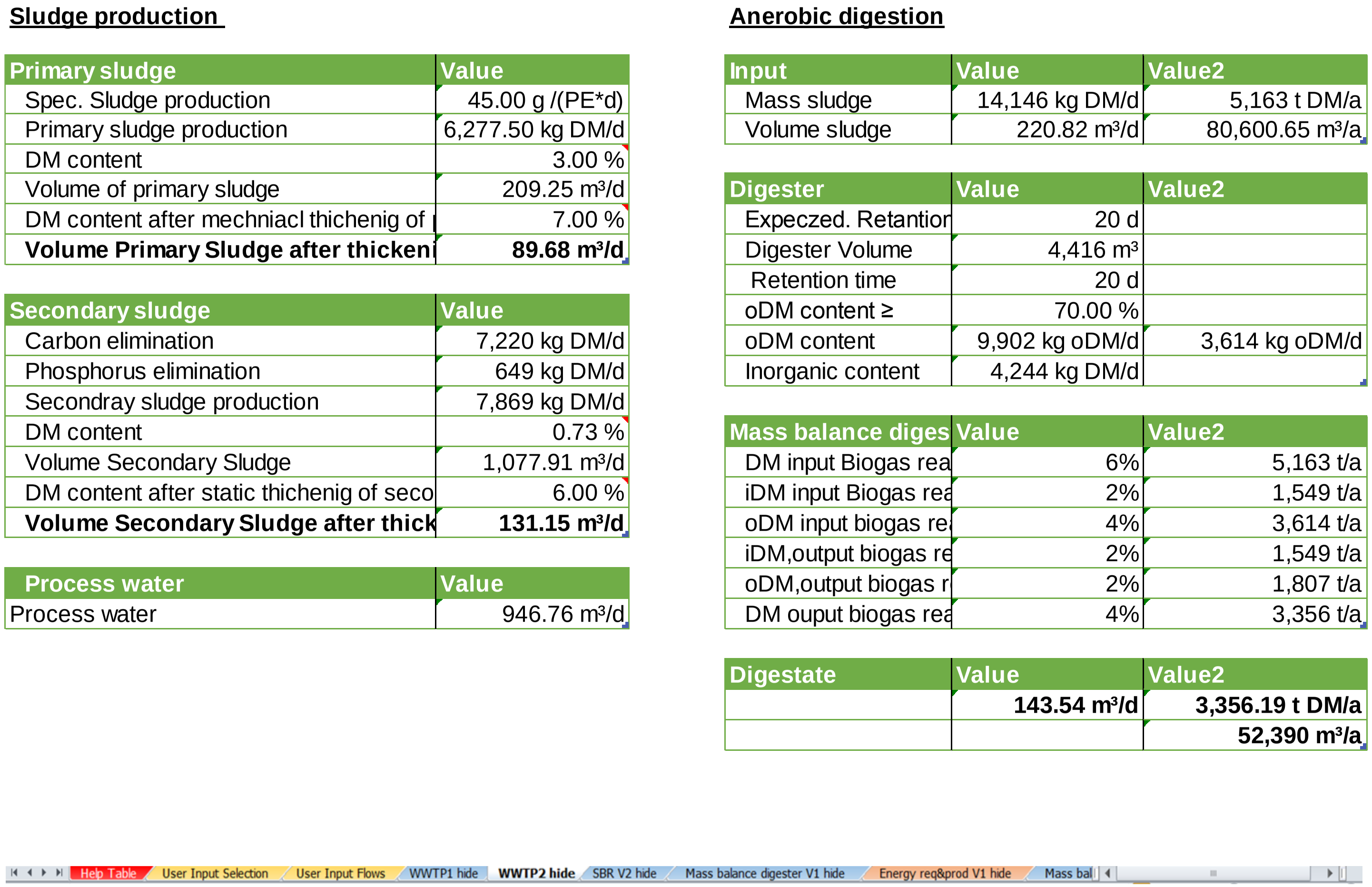
Biology

Secondray Sluge production	Formula	Value
Sluge age		11 d
S_d	$S_{d,C} + S_{d,P}$	

Carbon elimination	Formula	Value
$S_{d,C}$	$S_{C,BSB} * C_{d,BOD,biol}$	
F_T	$1{,}072^{(T-15)}$	0.812
$Cd,_{TS,biol}/Cd,_{BOD,biol}$		0.71
$S_{C,Bod}$		0.812 kg DM/kg BOD5
$S_{d,C}$		7,220 kg DM/d

Phosphorus elimination	Formula	Value
$S_{d,P}$	$Q_d * (3 * X_{P,BioP} + 6{,}8 * X_{P,prec,Fe} + 5{,}3 * X_{P,prec,Al})/1000$	
$C_{P,prec}$	$C_{P,biol} - C_{P,Aanaerobic} - X_{P,Biomass} - X_{P,BioP}$	
$C_{P,biol}$		11.19 mg/l
$C_{P,anaerobic}$		0.70 mg/l
$f_{P,AN}$		0.7
$C_{P,Bioass}$	$f_{P,BM} * C_{Bod,biol}$	4.46 mg/l
$f_{P,BM}$		0.01 kg P/kg BOD5
$C_{P,BioP}$	$f_{P,BioP} * C_{Bod,biol}$	2.23 mg/l
$f_{P,BioP}$		0.005
$c_{P,prec}$		3.80 mg/l
$L_{d,P,prec}$		75.84 kg P/d
$S_{d,P}$		649.103 kg TS/d
		0.073 kg TS/kg BSB5

Secondary Sluge production	Value
S_d	**7,869 kg TS/d**
	0.885 kg DM/kg BSB5



Sludge production

Primary sludge	Value
Spec. Sludge production	45.00 g /(PE*d)
Primary sludge production	6,277.50 kg DM/d
DM content	3.00 %
Volume of primary sludge	209.25 m³/d
DM content after mechniacl thichenig of ‖	7.00 %
Volume Primary Sludge after thickeni	**89.68 m³/d**

Secondary sludge	Value
Carbon elimination	7,220 kg DM/d
Phosphorus elimination	649 kg DM/d
Secondray sludge production	7,869 kg DM/d
DM content	0.73 %
Volume Secondary Sludge	1,077.91 m³/d
DM content after static thichenig of seco	6.00 %
Volume Secondary Sludge after thick	**131.15 m³/d**

Process water	Value
Process water	946.76 m³/d

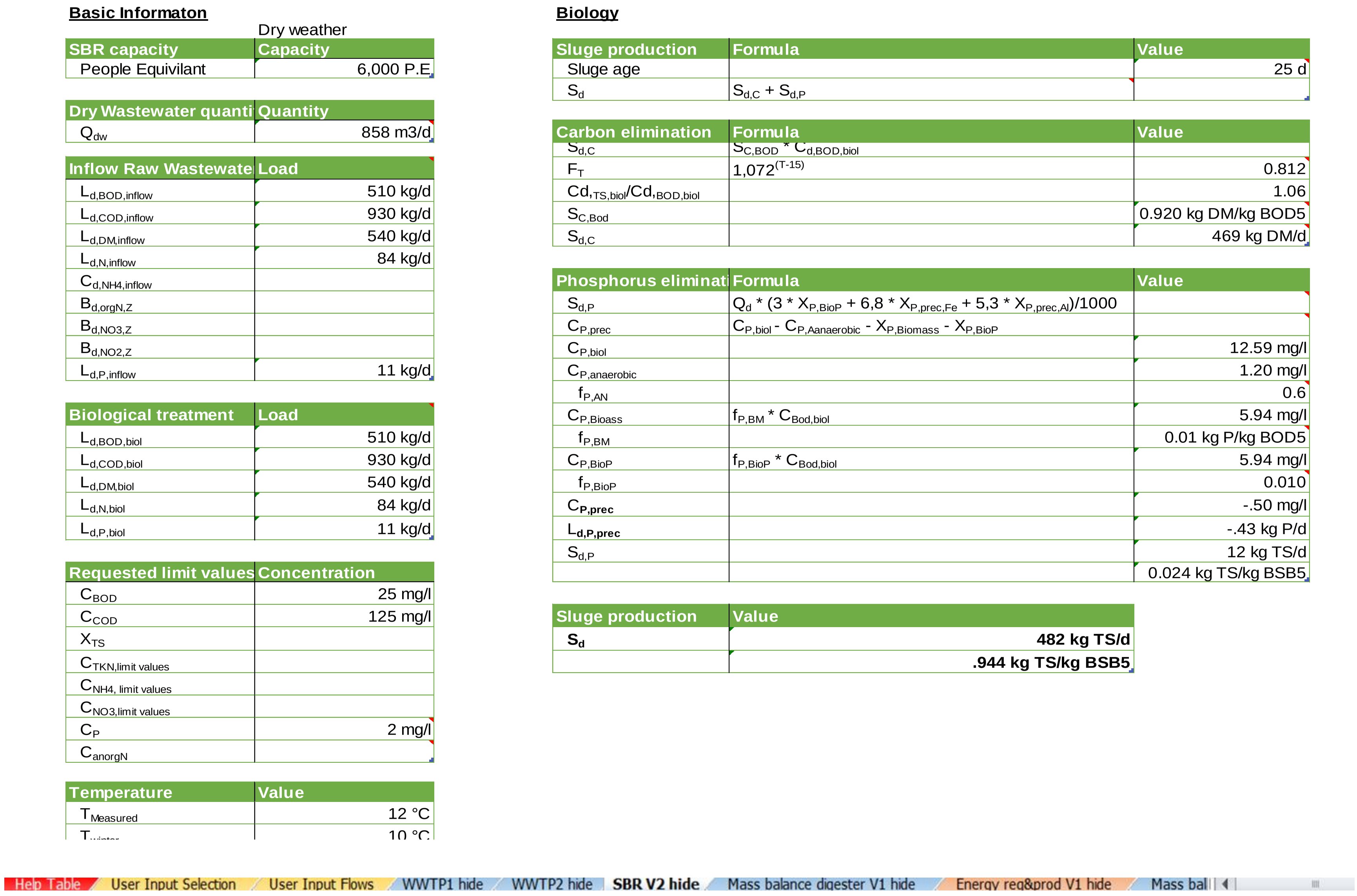
Anerobic digestion

Input	Value	Value2
Mass sludge	14,146 kg DM/d	5,163 t DM/a
Volume sludge	220.82 m³/d	80,600.65 m³/a

Digester	Value	Value2
Expeczed. Retantior	20 d	
Digester Volume	4,416 m³	
Retention time	20 d	
oDM content ≥	70.00 %	
oDM content	9,902 kg oDM/d	3,614 kg oDM/d
Inorganic content	4,244 kg DM/d	

Mass balance diges	Value	Value2
DM input Biogas rea	6%	5,163 t/a
iDM input Biogas rea	2%	1,549 t/a
oDM input biogas re	4%	3,614 t/a
iDM,output biogas re	2%	1,549 t/a
oDM,output biogas r	2%	1,807 t/a
DM ouput biogas rea	4%	3,356 t/a

Digestate	Value	Value2
	143.54 m³/d	**3,356.19 t DM/a**
		52,390 m³/a



Basic Informaton

Dry weather

SBR capacity	Capacity
People Equivilant	6,000 P.E

Dry Wastewater quanti	Quantity
Q_{dw}	858 m3/d

Inflow Raw Wastewate	Load
$L_{d,BOD,inflow}$	510 kg/d
$L_{d,COD,inflow}$	930 kg/d
$L_{d,DM,inflow}$	540 kg/d
$L_{d,N,inflow}$	84 kg/d
$C_{d,NH4,inflow}$	
$B_{d,orgN,Z}$	
$B_{d,NO3,Z}$	
$B_{d,NO2,Z}$	
$L_{d,P,inflow}$	11 kg/d

Biological treatment	Load
$L_{d,BOD,biol}$	510 kg/d
$L_{d,COD,biol}$	930 kg/d
$L_{d,DM,biol}$	540 kg/d
$L_{d,N,biol}$	84 kg/d
$L_{d,P,biol}$	11 kg/d

Requested limit values	Concentration
C_{BOD}	25 mg/l
C_{COD}	125 mg/l
X_{TS}	
$C_{TKN,limit\ values}$	
$C_{NH4,\ limit\ values}$	
$C_{NO3,limit\ values}$	
C_P	2 mg/l
C_{anorgN}	

Temperature	Value
$T_{Measured}$	12 °C
T	10 °C

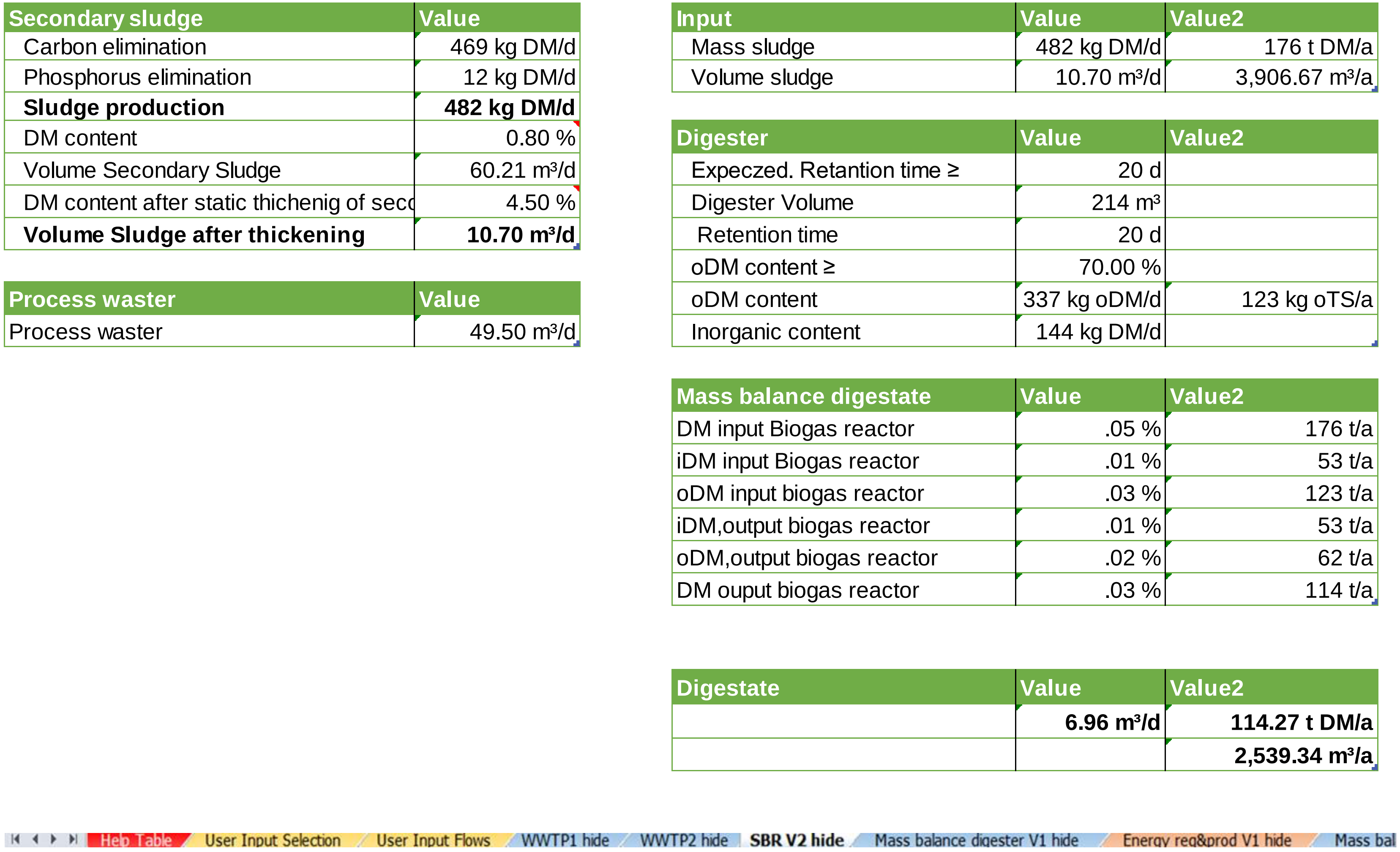
Biology

Sluge production	Formula	Value
Sluge age		25 d
S_d	$S_{d,C} + S_{d,P}$	

Carbon elimination	Formula	Value
$S_{d,C}$	$S_{C,BOD} * C_{d,BOD,biol}$	
F_T	$1{,}072^{(T-15)}$	0.812
$Cd,_{TS,biol}/Cd,_{BOD,biol}$		1.06
$S_{C,Bod}$		0.920 kg DM/kg BOD5
$S_{d,C}$		469 kg DM/d

Phosphorus eliminati	Formula	Value
$S_{d,P}$	$Q_d * (3 * X_{P,BioP} + 6{,}8 * X_{P,prec,Fe} + 5{,}3 * X_{P,prec,Al})/1000$	
$C_{P,prec}$	$C_{P,biol} - C_{P,Aanaerobic} - X_{P,Biomass} - X_{P,BioP}$	
$C_{P,biol}$		12.59 mg/l
$C_{P,anaerobic}$		1.20 mg/l
$f_{P,AN}$		0.6
$C_{P,Bioass}$	$f_{P,BM} * C_{Bod,biol}$	5.94 mg/l
$f_{P,BM}$		0.01 kg P/kg BOD5
$C_{P,BioP}$	$f_{P,BioP} * C_{Bod,biol}$	5.94 mg/l
$f_{P,BioP}$		0.010
$C_{\mathbf{P,prec}}$		-.50 mg/l
$L_{\mathbf{d,P,prec}}$		-.43 kg P/d
$S_{d,P}$		12 kg TS/d
		0.024 kg TS/kg BSB5

Sluge production	Value
$\mathbf{S_d}$	**482 kg TS/d**
	.944 kg TS/kg BSB5



Secondary sludge	Value
Carbon elimination	469 kg DM/d
Phosphorus elimination	12 kg DM/d
Sludge production	**482 kg DM/d**
DM content	0.80 %
Volume Secondary Sludge	60.21 m³/d
DM content after static thichenig of secc	4.50 %
Volume Sludge after thickening	**10.70 m³/d**

Process waster	Value
Process waster	49.50 m³/d

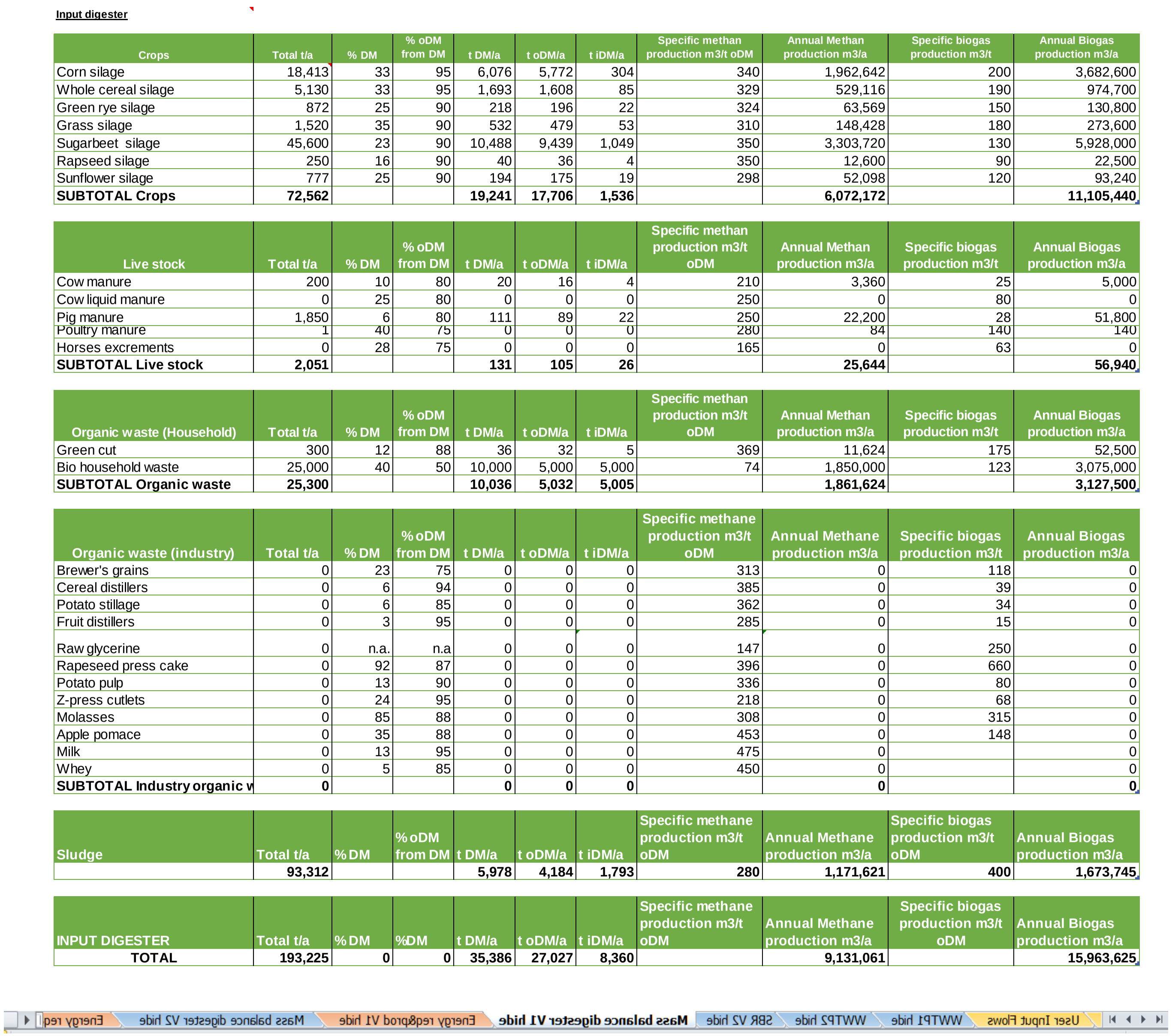
Input	Value	Value2
Mass sludge	482 kg DM/d	176 t DM/a
Volume sludge	10.70 m³/d	3,906.67 m³/a

Digester	Value	Value2
Expeczed. Retantion time ≥	20 d	
Digester Volume	214 m³	
Retention time	20 d	
oDM content ≥	70.00 %	
oDM content	337 kg oDM/d	123 kg oTS/a
Inorganic content	144 kg DM/d	

Mass balance digestate	Value	Value2
DM input Biogas reactor	.05 %	176 t/a
iDM input Biogas reactor	.01 %	53 t/a
oDM input biogas reactor	.03 %	123 t/a
iDM,output biogas reactor	.01 %	53 t/a
oDM,output biogas reactor	.02 %	62 t/a
DM ouput biogas reactor	.03 %	114 t/a

Digestate	Value	Value2
	6.96 m³/d	**114.27 t DM/a**
		2,539.34 m³/a

Appendix 6 – DST*, example of the Scenario d-4*



Input digester

Crops	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specific biogas production m3/t	Annual Biogas production m3/a
Corn silage	18,413	33	95	6,076	5,772	304	340	1,962,642	200	3,682,600
Whole cereal silage	5,130	33	95	1,693	1,608	85	329	529,116	190	974,700
Green rye silage	872	25	90	218	196	22	324	63,569	150	130,800
Grass silage	1,520	35	90	532	479	53	310	148,428	180	273,600
Sugarbeet silage	45,600	23	90	10,488	9,439	1,049	350	3,303,720	130	5,928,000
Rapseed silage	250	16	90	40	36	4	350	12,600	90	22,500
Sunflower silage	777	25	90	194	175	19	298	52,098	120	93,240
SUBTOTAL Crops	**72,562**			**19,241**	**17,706**	**1,536**		**6,072,172**		**11,105,440**

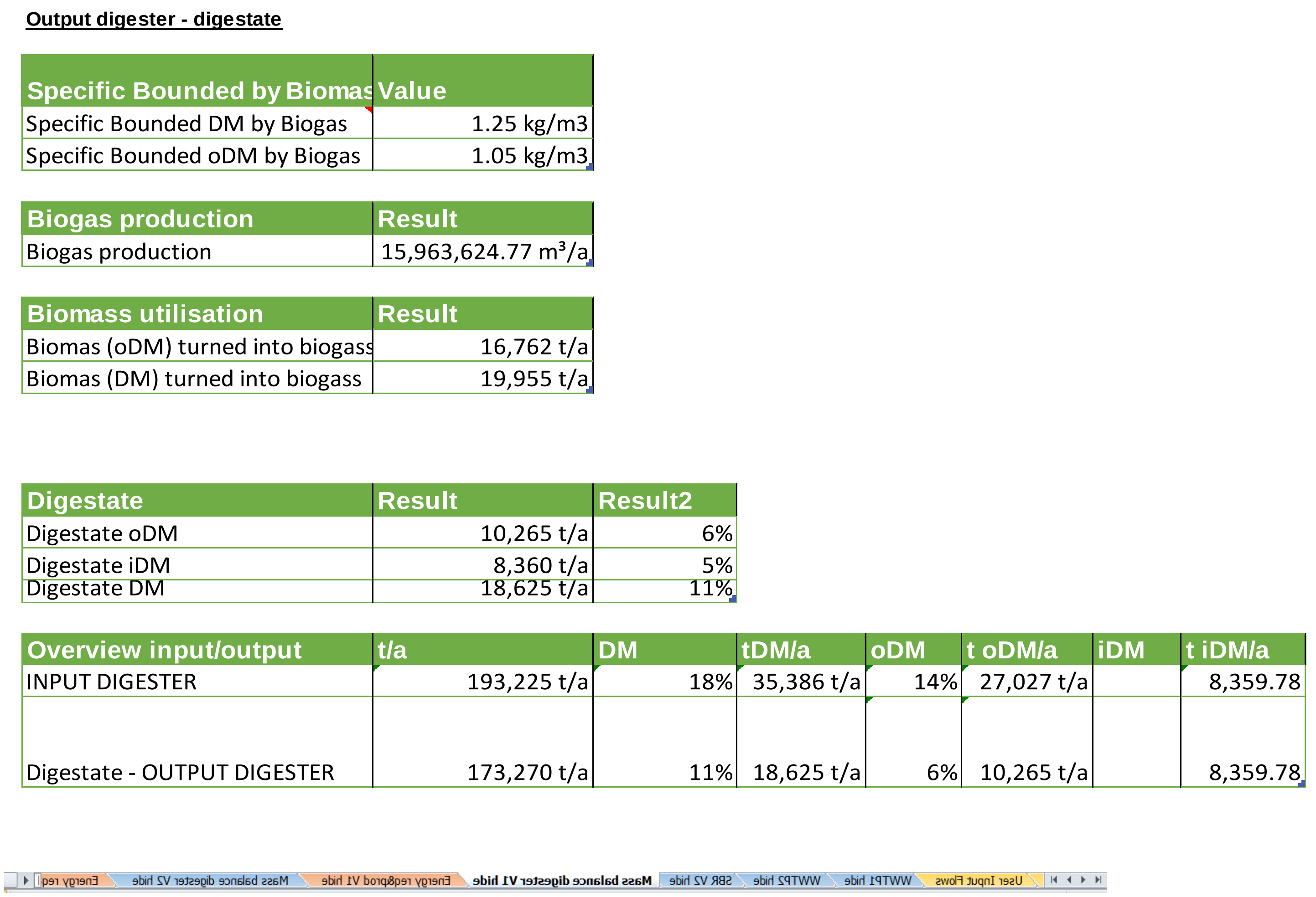
Live stock	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specific biogas production m3/t	Annual Biogas production m3/a
Cow manure	200	10	80	20	16	4	210	3,360	25	5,000
Cow liquid manure	0	25	80	0	0	0	250	0	80	0
Pig manure	1,850	6	80	111	89	22	250	22,200	28	51,800
Poultry manure	1	40	75	0	0	0	280	84	140	140
Horses excrements	0	28	75	0	0	0	165	0	63	0
SUBTOTAL Live stock	**2,051**			**131**	**105**	**26**		**25,644**		**56,940**

Organic waste (Household)	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specific biogas production m3/t	Annual Biogas production m3/a
Green cut	300	12	88	36	32	5	369	11,624	175	52,500
Bio household waste	25,000	40	50	10,000	5,000	5,000	74	1,850,000	123	3,075,000
SUBTOTAL Organic waste	**25,300**			**10,036**	**5,032**	**5,005**		**1,861,624**		**3,127,500**

Organic waste (industry)	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methane production m3/t oDM	Annual Methane production m3/a	Specific biogas production m3/t	Annual Biogas production m3/a
Brewer's grains	0	23	75	0	0	0	313	0	118	0
Cereal distillers	0	6	94	0	0	0	385	0	39	0
Potato stillage	0	6	85	0	0	0	362	0	34	0
Fruit distillers	0	3	95	0	0	0	285	0	15	0
Raw glycerine	0	n.a.	n.a	0	0	0	147	0	250	0
Rapeseed press cake	0	92	87	0	0	0	396	0	660	0
Potato pulp	0	13	90	0	0	0	336	0	80	0
Z-press cutlets	0	24	95	0	0	0	218	0	68	0
Molasses	0	85	88	0	0	0	308	0	315	0
Apple pomace	0	35	88	0	0	0	453	0	148	0
Milk	0	13	95	0	0	0	475	0		0
Whey	0	5	85	0	0	0	450	0		0
SUBTOTAL Industry organic w	**0**			**0**	**0**	**0**		**0**		**0**

Sludge	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methane production m3/t oDM	Annual Methane production m3/a	Specific biogas production m3/t oDM	Annual Biogas production m3/a
	93,312			**5,978**	**4,184**	**1,793**	**280**	**1,171,621**	**400**	**1,673,745**

INPUT DIGESTER	Total t/a	% DM	%DM	t DM/a	t oDM/a	t iDM/a	Specific methane production m3/t oDM	Annual Methane production m3/a	Specific biogas production m3/t oDM	Annual Biogas production m3/a
TOTAL	**193,225**	**0**	**0**	**35,386**	**27,027**	**8,360**		**9,131,061**		**15,963,625**



Output digester - digestate

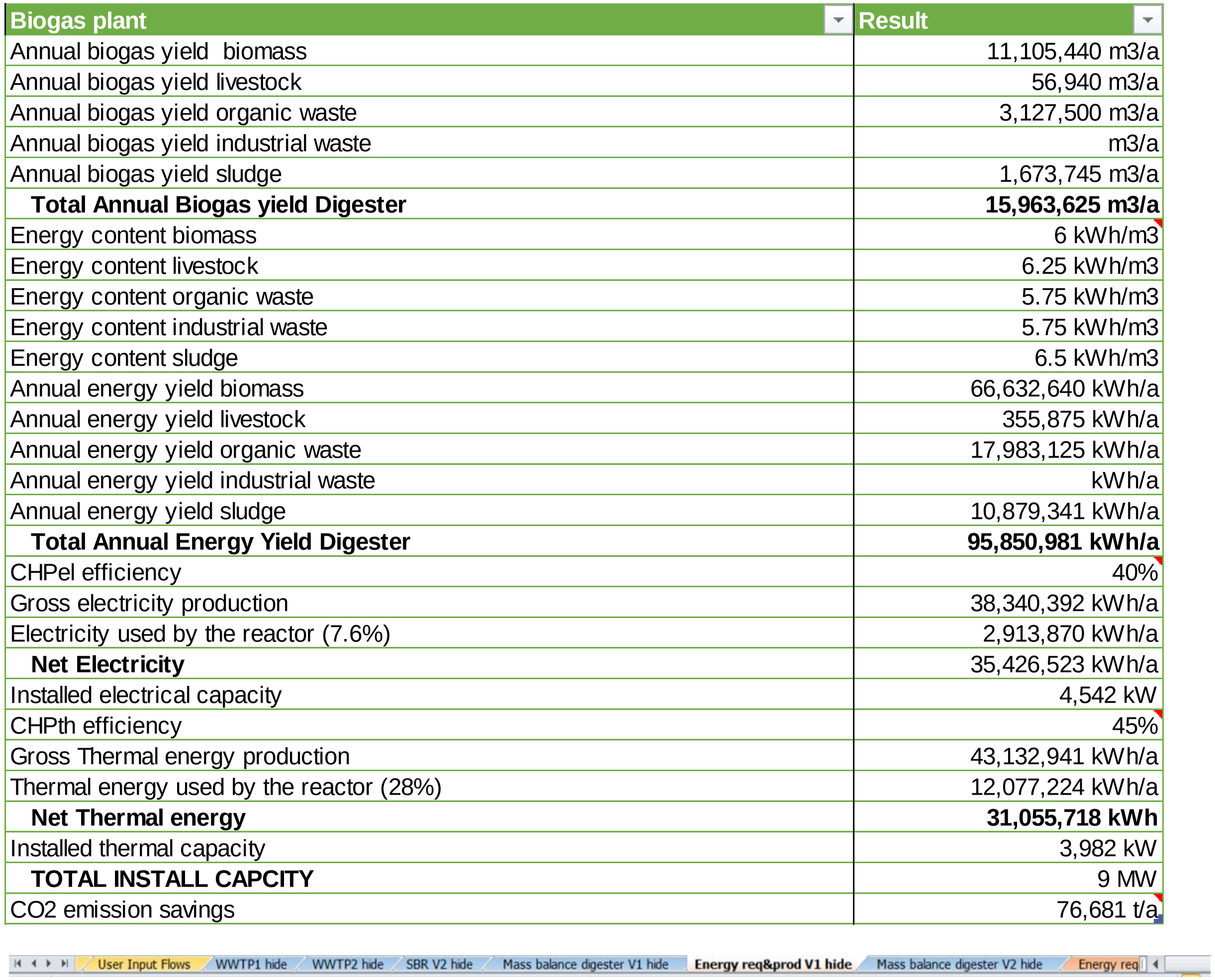
Specific Bounded by Biomas	Value
Specific Bounded DM by Biogas	1.25 kg/m3
Specific Bounded oDM by Biogas	1.05 kg/m3

Biogas production	Result
Biogas production	15,963,624.77 m³/a

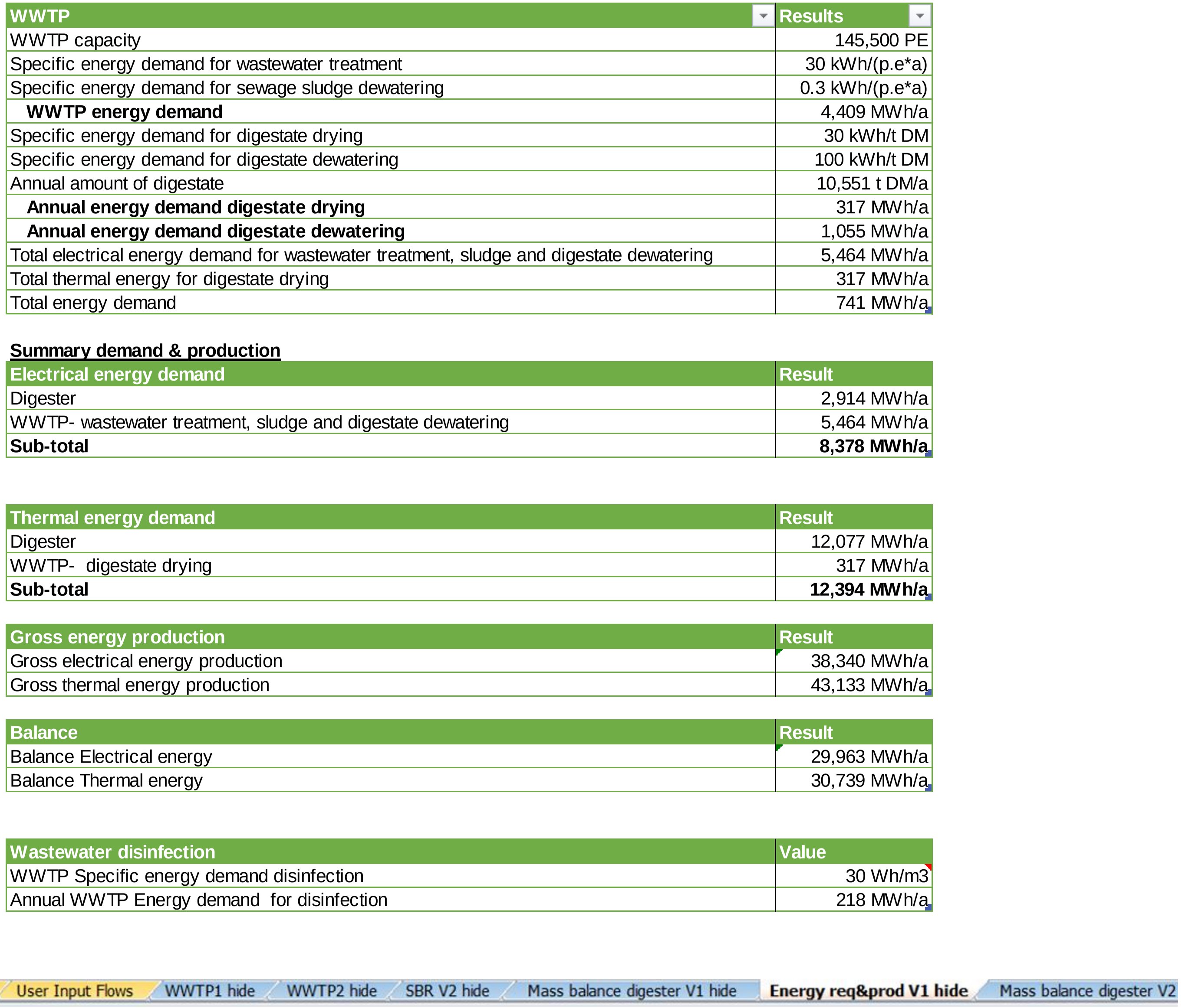
Biomass utilisation	Result
Biomas (oDM) turned into biogass	16,762 t/a
Biomas (DM) turned into biogass	19,955 t/a

Digestate	Result	Result2
Digestate oDM	10,265 t/a	6%
Digestate iDM	8,360 t/a	5%
Digestate DM	18,625 t/a	11%

Overview input/output	t/a	DM	tDM/a	oDM	t oDM/a	iDM	t iDM/a
INPUT DIGESTER	193,225 t/a	18%	35,386 t/a	14%	27,027 t/a		8,359.78
Digestate - OUTPUT DIGESTER	173,270 t/a	11%	18,625 t/a	6%	10,265 t/a		8,359.78



Biogas plant	Result
Annual biogas yield biomass	11,105,440 m3/a
Annual biogas yield livestock	56,940 m3/a
Annual biogas yield organic waste	3,127,500 m3/a
Annual biogas yield industrial waste	m3/a
Annual biogas yield sludge	1,673,745 m3/a
Total Annual Biogas yield Digester	**15,963,625 m3/a**
Energy content biomass	6 kWh/m3
Energy content livestock	6.25 kWh/m3
Energy content organic waste	5.75 kWh/m3
Energy content industrial waste	5.75 kWh/m3
Energy content sludge	6.5 kWh/m3
Annual energy yield biomass	66,632,640 kWh/a
Annual energy yield livestock	355,875 kWh/a
Annual energy yield organic waste	17,983,125 kWh/a
Annual energy yield industrial waste	kWh/a
Annual energy yield sludge	10,879,341 kWh/a
Total Annual Energy Yield Digester	**95,850,981 kWh/a**
CHPel efficiency	40%
Gross electricity production	38,340,392 kWh/a
Electricity used by the reactor (7.6%)	2,913,870 kWh/a
Net Electricity	35,426,523 kWh/a
Installed electrical capacity	4,542 kW
CHPth efficiency	45%
Gross Thermal energy production	43,132,941 kWh/a
Thermal energy used by the reactor (28%)	12,077,224 kWh/a
Net Thermal energy	**31,055,718 kWh**
Installed thermal capacity	3,982 kW
TOTAL INSTALL CAPCITY	9 MW
CO2 emission savings	76,681 t/a



WWTP	Results
WWTP capacity	145,500 PE
Specific energy demand for wastewater treatment	30 kWh/(p.e*a)
Specific energy demand for sewage sludge dewatering	0.3 kWh/(p.e*a)
WWTP energy demand	4,409 MWh/a
Specific energy demand for digestate drying	30 kWh/t DM
Specific energy demand for digestate dewatering	100 kWh/t DM
Annual amount of digestate	10,551 t DM/a
Annual energy demand digestate drying	317 MWh/a
Annual energy demand digestate dewatering	1,055 MWh/a
Total electrical energy demand for wastewater treatment, sludge and digestate dewatering	5,464 MWh/a
Total thermal energy for digestate drying	317 MWh/a
Total energy demand	741 MWh/a

Summary demand & production

Electrical energy demand	Result
Digester	2,914 MWh/a
WWTP- wastewater treatment, sludge and digestate dewatering	5,464 MWh/a
Sub-total	**8,378 MWh/a**

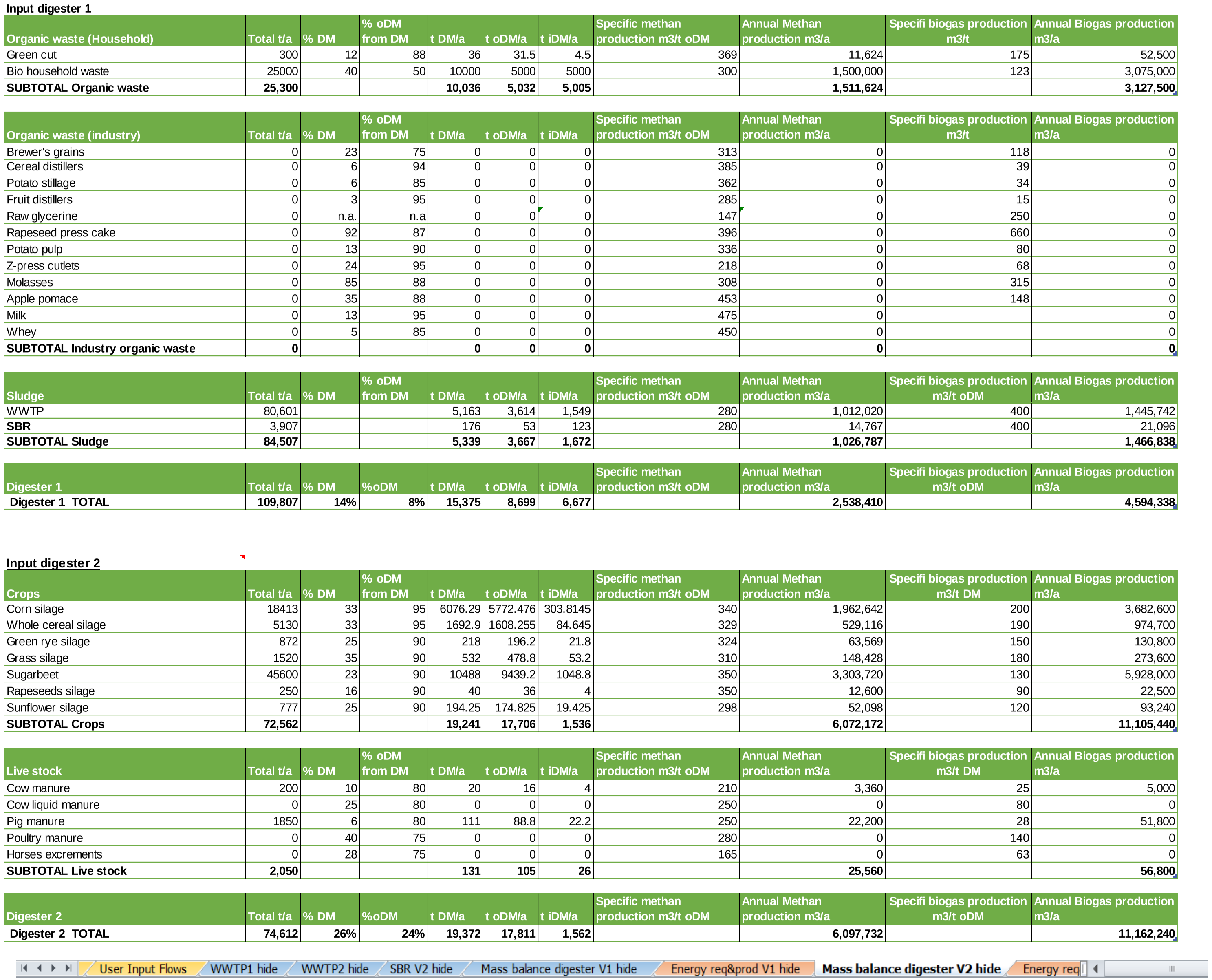
Thermal energy demand	Result
Digester	12,077 MWh/a
WWTP- digestate drying	317 MWh/a
Sub-total	**12,394 MWh/a**

Gross energy production	Result
Gross electrical energy production	38,340 MWh/a
Gross thermal energy production	43,133 MWh/a

Balance	Result
Balance Electrical energy	29,963 MWh/a
Balance Thermal energy	30,739 MWh/a

Wastewater disinfection	Value
WWTP Specific energy demand disinfection	30 Wh/m3
Annual WWTP Energy demand for disinfection	218 MWh/a

Appendix 6 – DST*, example of the Scenario d-4*



Input digester 1

Organic waste (Household)	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specifi biogas production m3/t	Annual Biogas production m3/a
Green cut	300	12	88	36	31.5	4.5	369	11,624	175	52,500
Bio household waste	25000	40	50	10000	5000	5000	300	1,500,000	123	3,075,000
SUBTOTAL Organic waste	**25,300**			**10,036**	**5,032**	**5,005**		**1,511,624**		**3,127,500**

Organic waste (industry)	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specifi biogas production m3/t	Annual Biogas production m3/a
Brewer's grains	0	23	75	0	0	0	313	0	118	0
Cereal distillers	0	6	94	0	0	0	385	0	39	0
Potato stillage	0	6	85	0	0	0	362	0	34	0
Fruit distillers	0	3	95	0	0	0	285	0	15	0
Raw glycerine	0	n.a.	n.a	0	0	0	147	0	250	0
Rapeseed press cake	0	92	87	0	0	0	396	0	660	0
Potato pulp	0	13	90	0	0	0	336	0	80	0
Z-press cutlets	0	24	95	0	0	0	218	0	68	0
Molasses	0	85	88	0	0	0	308	0	315	0
Apple pomace	0	35	88	0	0	0	453	0	148	0
Milk	0	13	95	0	0	0	475	0		0
Whey	0	5	85	0	0	0	450	0		0
SUBTOTAL Industry organic waste	**0**			**0**	**0**	**0**		**0**		**0**

Sludge	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specifi biogas production m3/t oDM	Annual Biogas production m3/a
WWTP	80,601			5,163	3,614	1,549	280	1,012,020	400	1,445,742
SBR	3,907			176	53	123	280	14,767	400	21,096
SUBTOTAL Sludge	**84,507**			**5,339**	**3,667**	**1,672**		**1,026,787**		**1,466,838**

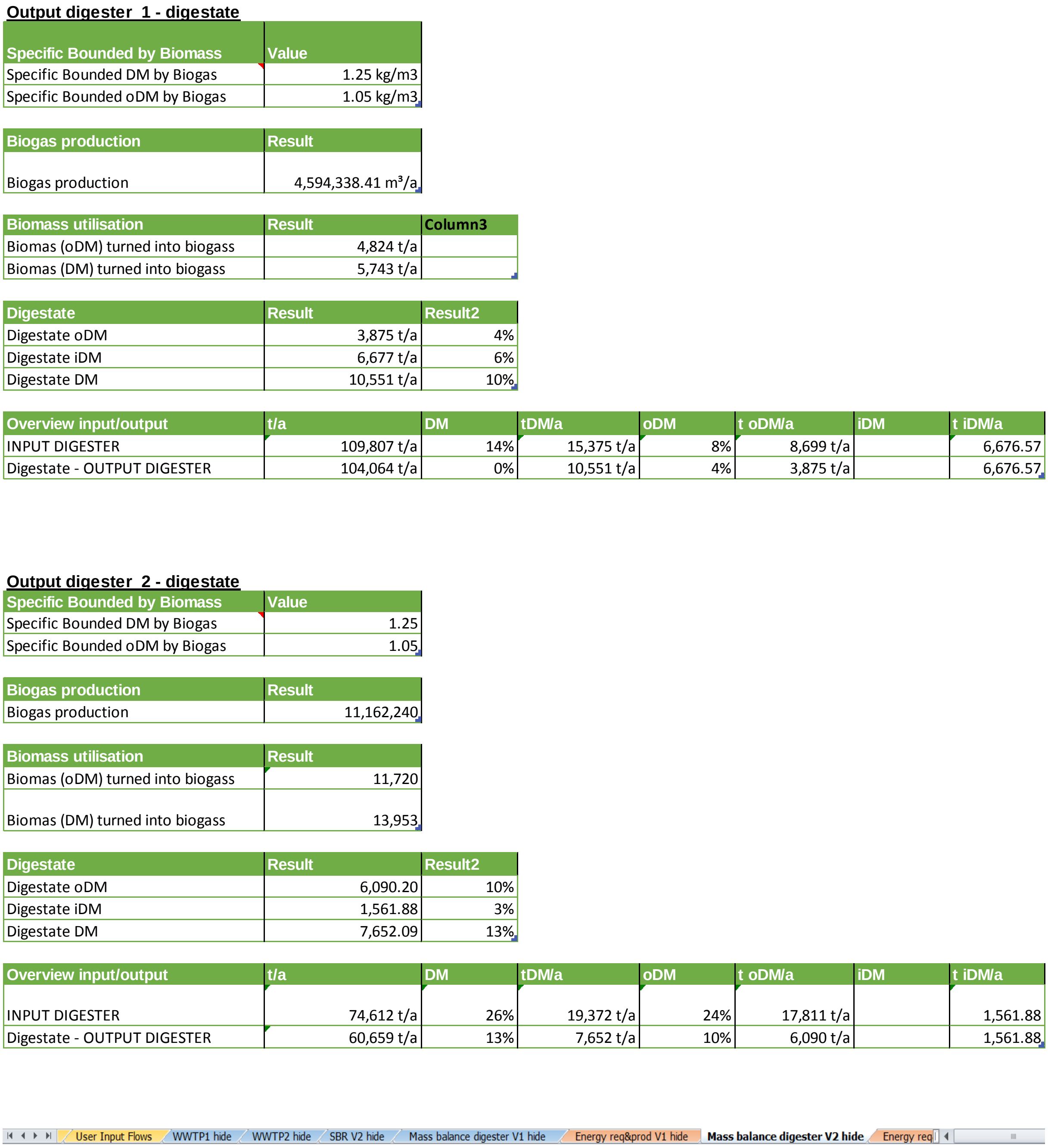
Digester 1	Total t/a	% DM	%oDM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specifi biogas production m3/t oDM	Annual Biogas production m3/a
Digester 1 TOTAL	**109,807**	**14%**	**8%**	**15,375**	**8,699**	**6,677**		**2,538,410**		**4,594,338**

Input digester 2

Crops	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specifi biogas production m3/t DM	Annual Biogas production m3/a
Corn silage	18413	33	95	6076.29	5772.476	303.8145	340	1,962,642	200	3,682,600
Whole cereal silage	5130	33	95	1692.9	1608.255	84.645	329	529,116	190	974,700
Green rye silage	872	25	90	218	196.2	21.8	324	63,569	150	130,800
Grass silage	1520	35	90	532	478.8	53.2	310	148,428	180	273,600
Sugarbeet	45600	23	90	10488	9439.2	1048.8	350	3,303,720	130	5,928,000
Rapeseeds silage	250	16	90	40	36	4	350	12,600	90	22,500
Sunflower silage	777	25	90	194.25	174.825	19.425	298	52,098	120	93,240
SUBTOTAL Crops	**72,562**			**19,241**	**17,706**	**1,536**		**6,072,172**		**11,105,440**

Live stock	Total t/a	% DM	% oDM from DM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specifi biogas production m3/t DM	Annual Biogas production m3/a
Cow manure	200	10	80	20	16	4	210	3,360	25	5,000
Cow liquid manure	0	25	80	0	0	0	250	0	80	0
Pig manure	1850	6	80	111	88.8	22.2	250	22,200	28	51,800
Poultry manure	0	40	75	0	0	0	280	0	140	0
Horses excrements	0	28	75	0	0	0	165	0	63	0
SUBTOTAL Live stock	**2,050**			**131**	**105**	**26**		**25,560**		**56,800**

Digester 2	Total t/a	% DM	%oDM	t DM/a	t oDM/a	t iDM/a	Specific methan production m3/t oDM	Annual Methan production m3/a	Specifi biogas production m3/t oDM	Annual Biogas production m3/a
Digester 2 TOTAL	**74,612**	**26%**	**24%**	**19,372**	**17,811**	**1,562**		**6,097,732**		**11,162,240**



Output digester 1 - digestate

Specific Bounded by Biomass	Value
Specific Bounded DM by Biogas	1.25 kg/m3
Specific Bounded oDM by Biogas	1.05 kg/m3

Biogas production	Result
Biogas production	4,594,338.41 m³/a

Biomass utilisation	Result	Column3
Biomas (oDM) turned into biogass	4,824 t/a	
Biomas (DM) turned into biogass	5,743 t/a	

Digestate	Result	Result2
Digestate oDM	3,875 t/a	4%
Digestate iDM	6,677 t/a	6%
Digestate DM	10,551 t/a	10%

Overview input/output	t/a	DM	tDM/a	oDM	t oDM/a	iDM	t iDM/a
INPUT DIGESTER	109,807 t/a	14%	15,375 t/a	8%	8,699 t/a		6,676.57
Digestate - OUTPUT DIGESTER	104,064 t/a	0%	10,551 t/a	4%	3,875 t/a		6,676.57

Output digester 2 - digestate

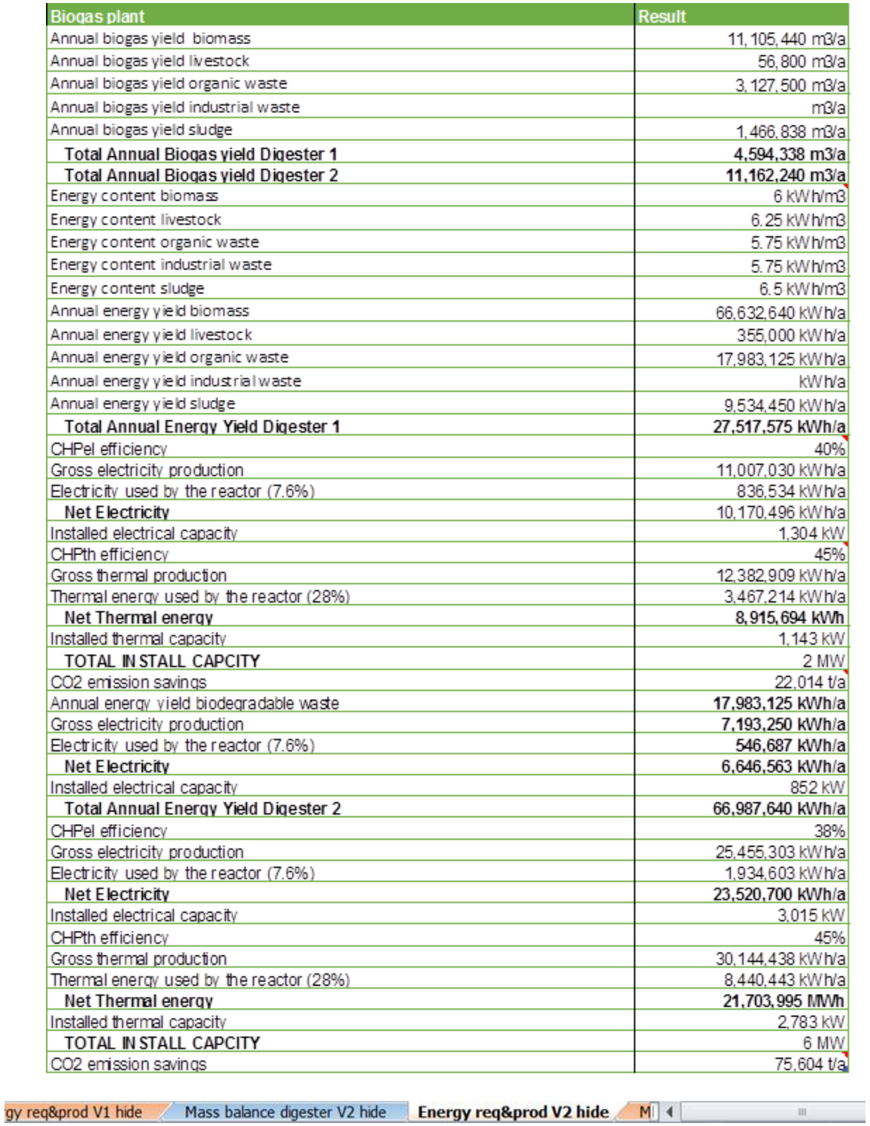
Specific Bounded by Biomass	Value
Specific Bounded DM by Biogas	1.25
Specific Bounded oDM by Biogas	1.05

Biogas production	Result
Biogas production	11,162,240

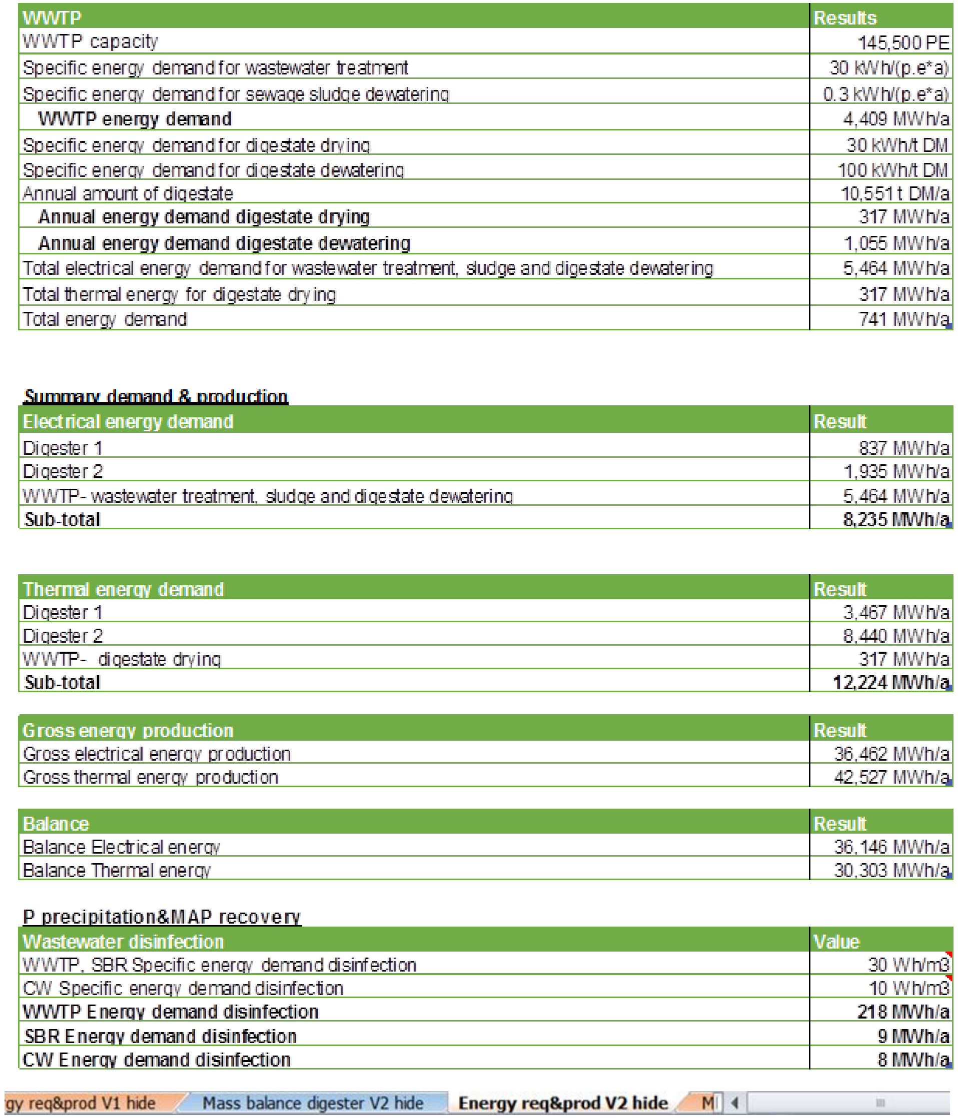
Biomass utilisation	Result
Biomas (oDM) turned into biogass	11,720
Biomas (DM) turned into biogass	13,953

Digestate	Result	Result2
Digestate oDM	6,090.20	10%
Digestate iDM	1,561.88	3%
Digestate DM	7,652.09	13%

Overview input/output	t/a	DM	tDM/a	oDM	t oDM/a	iDM	t iDM/a
INPUT DIGESTER	74,612 t/a	26%	19,372 t/a	24%	17,811 t/a		1,561.88
Digestate - OUTPUT DIGESTER	60,659 t/a	13%	7,652 t/a	10%	6,090 t/a		1,561.88



Biogas plant	Result
Annual biogas yield biomass	11,105,440 m3/a
Annual biogas yield livestock	56,800 m3/a
Annual biogas yield organic waste	3,127,500 m3/a
Annual biogas yield industrial waste	m3/a
Annual biogas yield sludge	1,466,838 m3/a
Total Annual Biogas yield Digester 1	**4,594,338 m3/a**
Total Annual Biogas yield Digester 2	**11,162,240 m3/a**
Energy content biomass	6 kWh/m3
Energy content livestock	6.25 kWh/m3
Energy content organic waste	5.75 kWh/m3
Energy content industrial waste	5.75 kWh/m3
Energy content sludge	6.5 kWh/m3
Annual energy yield biomass	66,632,640 kWh/a
Annual energy yield livestock	355,000 kWh/a
Annual energy yield organic waste	17,983,125 kWh/a
Annual energy yield industrial waste	kWh/a
Annual energy yield sludge	9,534,450 kWh/a
Total Annual Energy Yield Digester 1	**27,517,575 kWh/a**
CHPel efficiency	40%
Gross electricity production	11,007,030 kWh/a
Electricity used by the reactor (7.6%)	836,534 kWh/a
Net Electricity	10,170,496 kWh/a
Installed electrical capacity	1,304 kW
CHPth efficiency	45%
Gross thermal production	12,382,909 kWh/a
Thermal energy used by the reactor (28%)	3,467,214 kWh/a
Net Thermal energy	**8,915,694 kWh**
Installed thermal capacity	1,143 kW
TOTAL INSTALL CAPCITY	2 MW
CO2 emission savings	22,014 t/a
Annual energy yield biodegradable waste	**17,983,125 kWh/a**
Gross electricity production	**7,193,250 kWh/a**
Electricity used by the reactor (7.6%)	**546,687 kWh/a**
Net Electricity	**6,646,563 kWh/a**
Installed electrical capacity	852 kW
Total Annual Energy Yield Digester 2	**66,987,640 kWh/a**
CHPel efficiency	38%
Gross electricity production	25,455,303 kWh/a
Electricity used by the reactor (7.6%)	1,934,603 kWh/a
Net Electricity	**23,520,700 kWh/a**
Installed electrical capacity	3,015 kW
CHPth efficiency	45%
Gross thermal production	30,144,438 kWh/a
Thermal energy used by the reactor (28%)	8,440,443 kWh/a
Net Thermal energy	**21,703,995 MWh**
Installed thermal capacity	2,783 kW
TOTAL INSTALL CAPCITY	6 MW
CO2 emission savings	75,604 t/a



WWTP	Results
WWTP capacity	145,500 PE
Specific energy demand for wastewater treatment	30 kWh/(p.e*a)
Specific energy demand for sewage sludge dewatering	0.3 kWh/(p.e*a)
WWTP energy demand	4,409 MWh/a
Specific energy demand for digestate drying	30 kWh/t DM
Specific energy demand for digestate dewatering	100 kWh/t DM
Annual amount of digestate	10,551 t DM/a
Annual energy demand digestate drying	317 MWh/a
Annual energy demand digestate dewatering	1,055 MWh/a
Total electrical energy demand for wastewater treatment, sludge and digestate dewatering	5,464 MWh/a
Total thermal energy for digestate drying	317 MWh/a
Total energy demand	741 MWh/a

Summary demand & production

Electrical energy demand	Result
Digester 1	837 MWh/a
Digester 2	1,935 MWh/a
WWTP- wastewater treatment, sludge and digestate dewatering	5,464 MWh/a
Sub-total	**8,235 MWh/a**

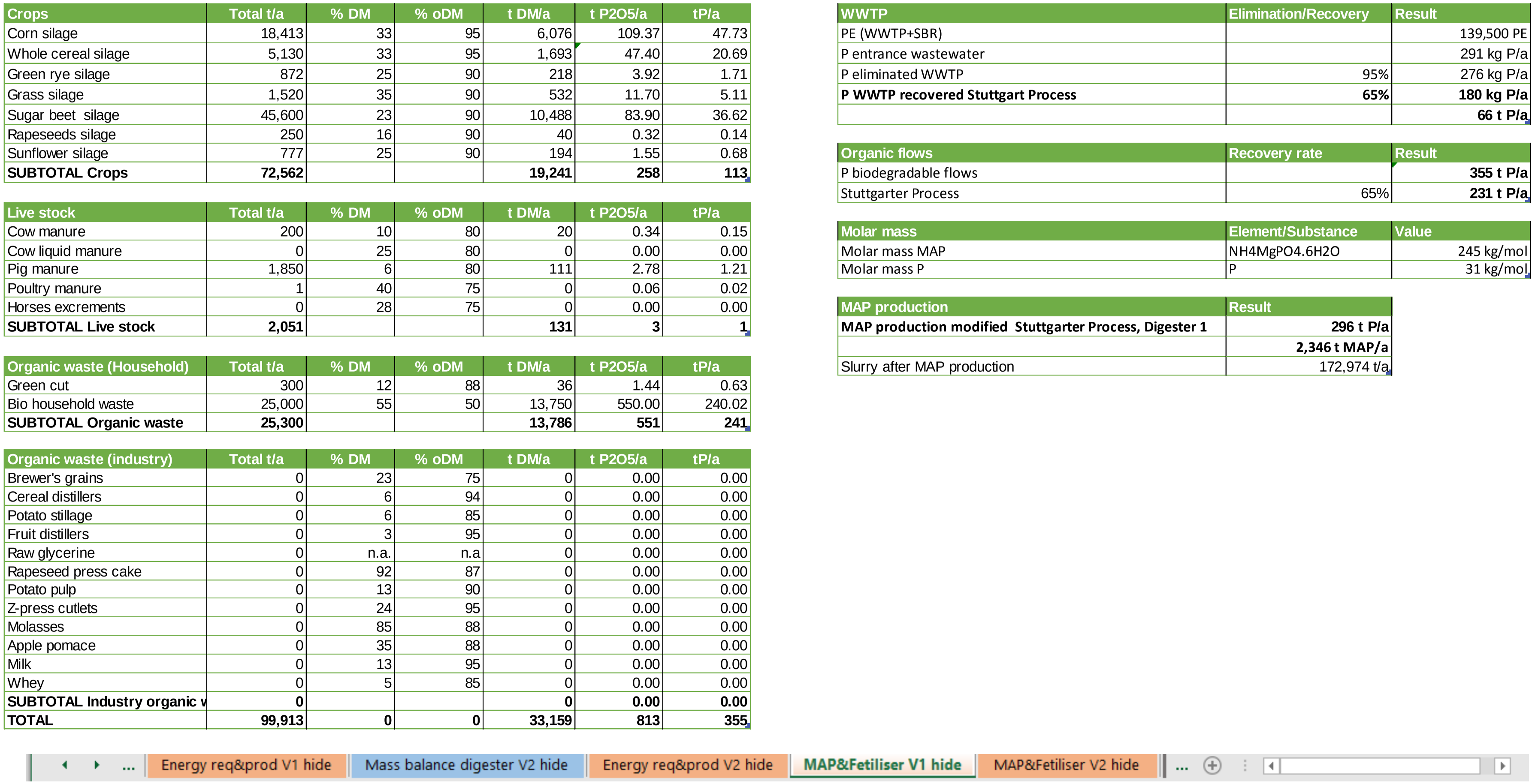
Thermal energy demand	Result
Digester 1	3,467 MWh/a
Digester 2	8,440 MWh/a
WWTP- digestate drying	317 MWh/a
Sub-total	**12,224 MWh/a**

Gross energy production	Result
Gross electrical energy production	36,462 MWh/a
Gross thermal energy production	42,527 MWh/a

Balance	Result
Balance Electrical energy	36,146 MWh/a
Balance Thermal energy	30,303 MWh/a

P precipitation&MAP recovery

Wastewater disinfection	Value
WWTP, SBR Specific energy demand disinfection	30 Wh/m3
CW Specific energy demand disinfection	10 Wh/m3
WWTP Energy demand disinfection	**218 MWh/a**
SBR Energy demand disinfection	**9 MWh/a**
CW Energy demand disinfection	**8 MWh/a**



Crops	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Corn silage	18,413	33	95	6,076	109.37	47.73
Whole cereal silage	5,130	33	95	1,693	47.40	20.69
Green rye silage	872	25	90	218	3.92	1.71
Grass silage	1,520	35	90	532	11.70	5.11
Sugar beet silage	45,600	23	90	10,488	83.90	36.62
Rapeseeds silage	250	16	90	40	0.32	0.14
Sunflower silage	777	25	90	194	1.55	0.68
SUBTOTAL Crops	**72,562**			**19,241**	**258**	**113**

Live stock	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Cow manure	200	10	80	20	0.34	0.15
Cow liquid manure	0	25	80	0	0.00	0.00
Pig manure	1,850	6	80	111	2.78	1.21
Poultry manure	1	40	75	0	0.06	0.02
Horses excrements	0	28	75	0	0.00	0.00
SUBTOTAL Live stock	**2,051**			**131**	**3**	**1**

Organic waste (Household)	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Green cut	300	12	88	36	1.44	0.63
Bio household waste	25,000	55	50	13,750	550.00	240.02
SUBTOTAL Organic waste	**25,300**			**13,786**	**551**	**241**

Organic waste (industry)	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Brewer's grains	0	23	75	0	0.00	0.00
Cereal distillers	0	6	94	0	0.00	0.00
Potato stillage	0	6	85	0	0.00	0.00
Fruit distillers	0	3	95	0	0.00	0.00
Raw glycerine	0	n.a.	n.a	0	0.00	0.00
Rapeseed press cake	0	92	87	0	0.00	0.00
Potato pulp	0	13	90	0	0.00	0.00
Z-press cutlets	0	24	95	0	0.00	0.00
Molasses	0	85	88	0	0.00	0.00
Apple pomace	0	35	88	0	0.00	0.00
Milk	0	13	95	0	0.00	0.00
Whey	0	5	85	0	0.00	0.00
SUBTOTAL Industry organic v	**0**			**0**	**0.00**	**0.00**
TOTAL	**99,913**	**0**	**0**	**33,159**	**813**	**355**

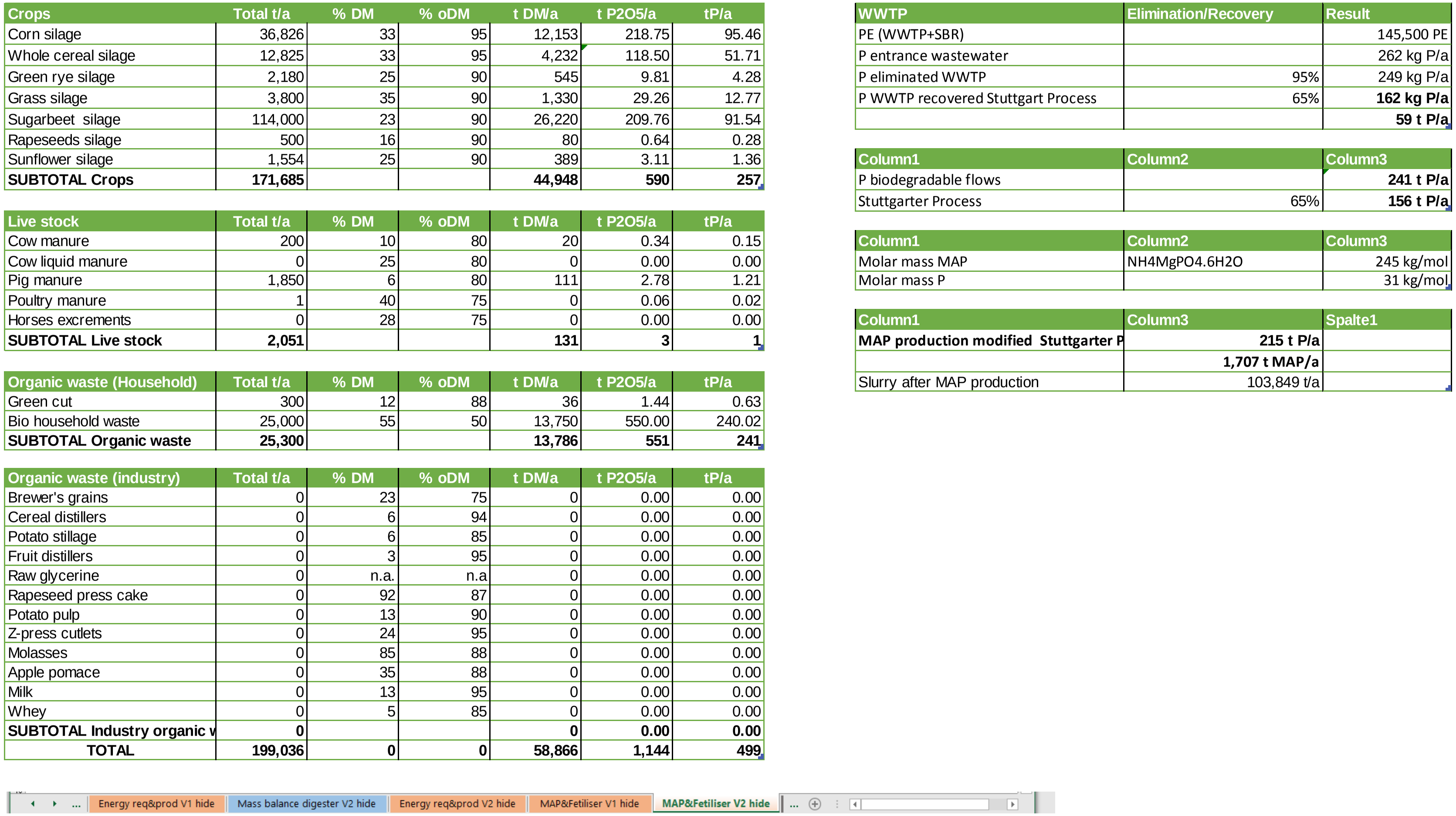
WWTP	Elimination/Recovery	Result
PE (WWTP+SBR)		139,500 PE
P entrance wastewater		291 kg P/a
P eliminated WWTP	95%	276 kg P/a
P WWTP recovered Stuttgart Process	**65%**	**180 kg P/a**
		66 t P/a

Organic flows	Recovery rate	Result
P biodegradable flows		**355 t P/a**
Stuttgarter Process	65%	**231 t P/a**

Molar mass	Element/Substance	Value
Molar mass MAP	NH4MgPO4.6H2O	245 kg/mol
Molar mass P	P	31 kg/mol

MAP production	Result
MAP production modified Stuttgarter Process, Digester 1	**296 t P/a**
	2,346 t MAP/a
Slurry after MAP production	172,974 t/a

Appendix 6 – DST, *example of the Scenario d-4*



Crops	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Corn silage	36,826	33	95	12,153	218.75	95.46
Whole cereal silage	12,825	33	95	4,232	118.50	51.71
Green rye silage	2,180	25	90	545	9.81	4.28
Grass silage	3,800	35	90	1,330	29.26	12.77
Sugarbeet silage	114,000	23	90	26,220	209.76	91.54
Rapeseeds silage	500	16	90	80	0.64	0.28
Sunflower silage	1,554	25	90	389	3.11	1.36
SUBTOTAL Crops	**171,685**			**44,948**	**590**	**257**

Live stock	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Cow manure	200	10	80	20	0.34	0.15
Cow liquid manure	0	25	80	0	0.00	0.00
Pig manure	1,850	6	80	111	2.78	1.21
Poultry manure	1	40	75	0	0.06	0.02
Horses excrements	0	28	75	0	0.00	0.00
SUBTOTAL Live stock	**2,051**			**131**	**3**	**1**

Organic waste (Household)	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Green cut	300	12	88	36	1.44	0.63
Bio household waste	25,000	55	50	13,750	550.00	240.02
SUBTOTAL Organic waste	**25,300**			**13,786**	**551**	**241**

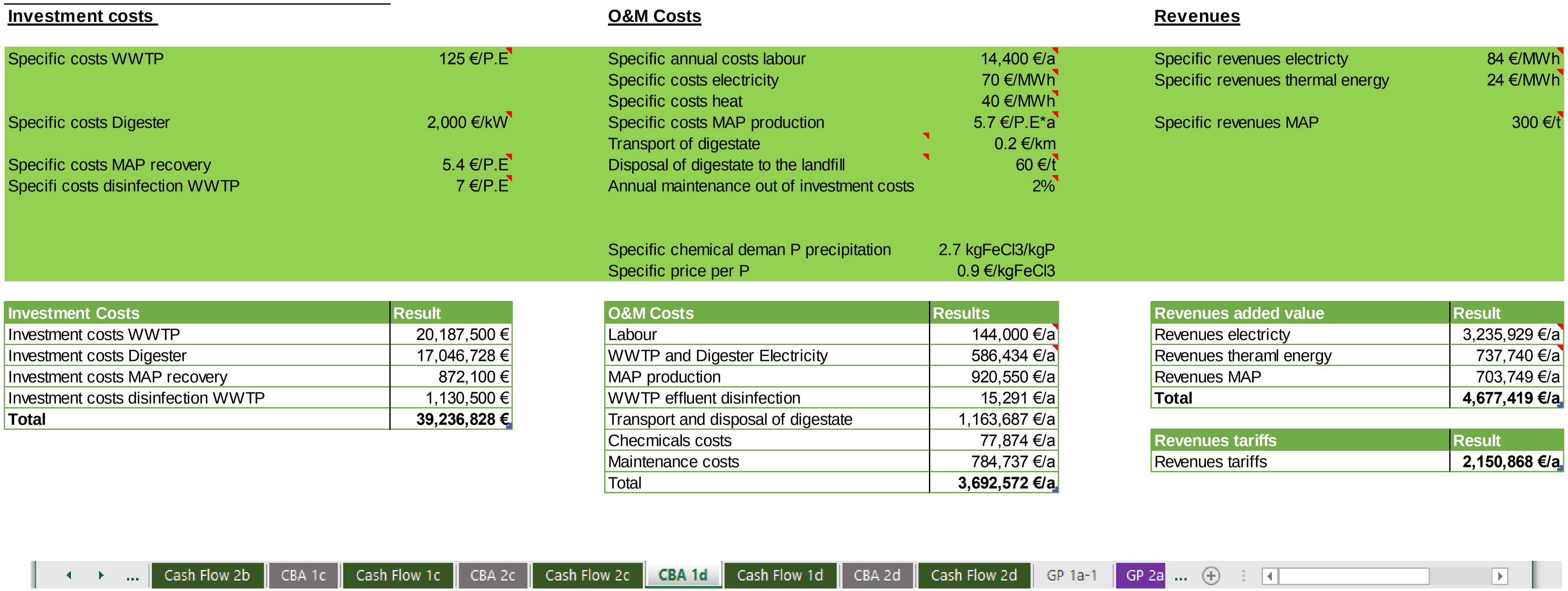
Organic waste (industry)	Total t/a	% DM	% oDM	t DM/a	t P2O5/a	tP/a
Brewer's grains	0	23	75	0	0.00	0.00
Cereal distillers	0	6	94	0	0.00	0.00
Potato stillage	0	6	85	0	0.00	0.00
Fruit distillers	0	3	95	0	0.00	0.00
Raw glycerine	0	n.a.	n.a	0	0.00	0.00
Rapeseed press cake	0	92	87	0	0.00	0.00
Potato pulp	0	13	90	0	0.00	0.00
Z-press cutlets	0	24	95	0	0.00	0.00
Molasses	0	85	88	0	0.00	0.00
Apple pomace	0	35	88	0	0.00	0.00
Milk	0	13	95	0	0.00	0.00
Whey	0	5	85	0	0.00	0.00
SUBTOTAL Industry organic v	**0**			**0**	**0.00**	**0.00**
TOTAL	**199,036**	**0**	**0**	**58,866**	**1,144**	**499**

WWTP	Elimination/Recovery	Result
PE (WWTP+SBR)		145,500 PE
P entrance wastewater		262 kg P/a
P eliminated WWTP	95%	249 kg P/a
P WWTP recovered Stuttgart Process	65%	**162 kg P/a**
		59 t P/a

Column1	Column2	Column3
P biodegradable flows		**241 t P/a**
Stuttgarter Process	65%	**156 t P/a**

Column1	Column2	Column3
Molar mass MAP	NH4MgPO4.6H2O	245 kg/mol
Molar mass P		31 kg/mol

Column1	Column3	Spalte1
MAP production modified Stuttgarter P	**215 t P/a**	
	1,707 t MAP/a	
Slurry after MAP production	103,849 t/a	



Investment costs

Specific costs WWTP	125 €/P.E
Specific costs Digester	2,000 €/kW
Specific costs MAP recovery	5.4 €/P.E
Specifi costs disinfection WWTP	7 €/P.E

O&M Costs

Specific annual costs labour	14,400 €/a
Specific costs electricity	70 €/MWh
Specific costs heat	40 €/MWh
Specific costs MAP production	5.7 €/P.E*a
Transport of digestate	0.2 €/km
Disposal of digestate to the landfill	60 €/t
Annual maintenance out of investment costs	2%
Specific chemical deman P precipitation	2.7 kgFeCl3/kgP
Specific price per P	0.9 €/kgFeCl3

Revenues

Specific revenues electricty	84 €/MWh
Specific revenues thermal energy	24 €/MWh
Specific revenues MAP	300 €/t

Investment Costs	Result
Investment costs WWTP	20,187,500 €
Investment costs Digester	17,046,728 €
Investment costs MAP recovery	872,100 €
Investment costs disinfection WWTP	1,130,500 €
Total	**39,236,828 €**

O&M Costs	Results
Labour	144,000 €/a
WWTP and Digester Electricity	586,434 €/a
MAP production	920,550 €/a
WWTP effluent disinfection	15,291 €/a
Transport and disposal of digestate	1,163,687 €/a
Checmicals costs	77,874 €/a
Maintenance costs	784,737 €/a
Total	**3,692,572 €/a**

Revenues added value	Result
Revenues electricty	3,235,929 €/a
Revenues theraml energy	737,740 €/a
Revenues MAP	703,749 €/a
Total	**4,677,419 €/a**

Revenues tariffs	Result
Revenues tariffs	**2,150,868 €/a**

Appendix 6 – DST*, example of the Scenario d-4*

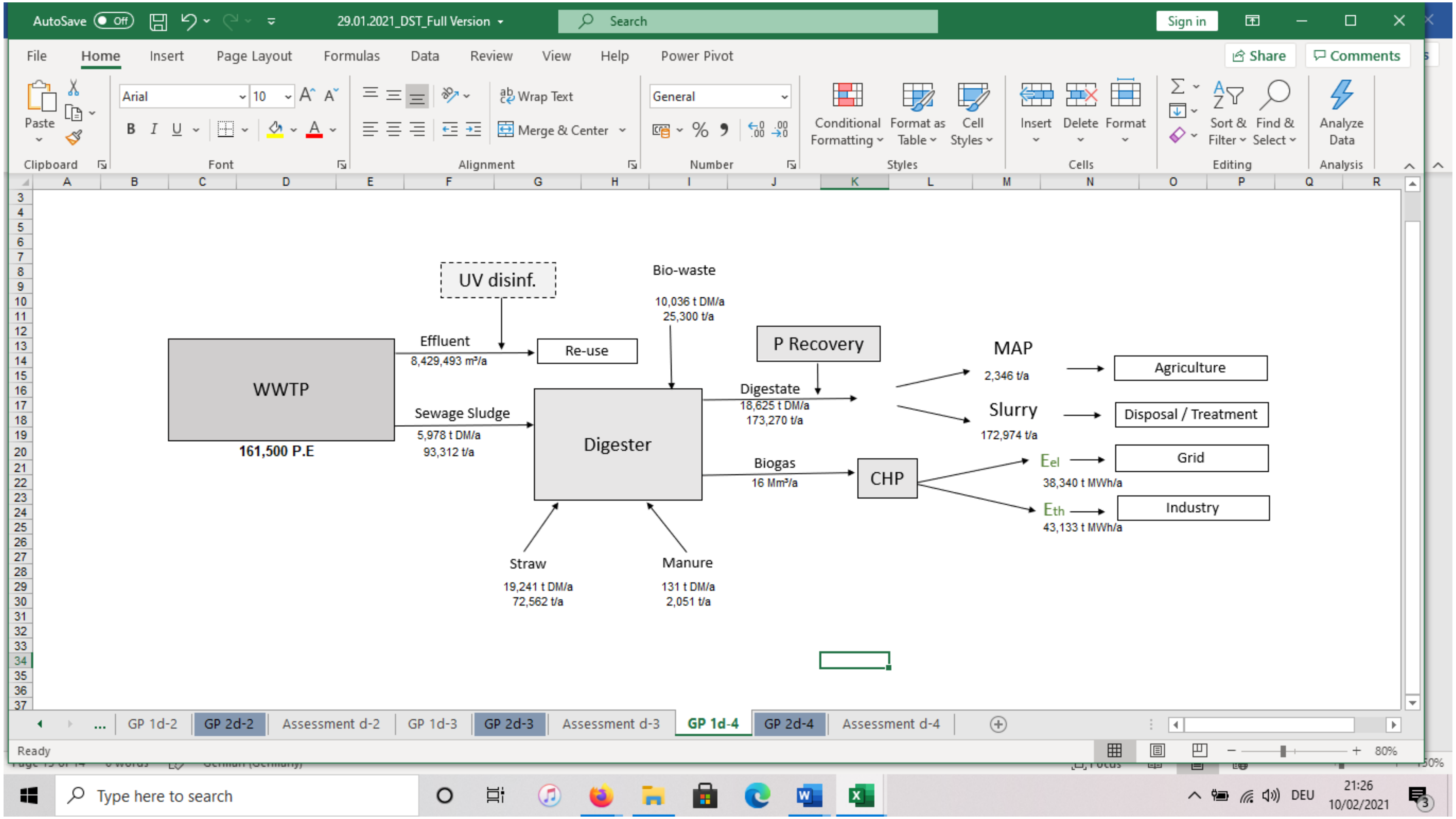
Years	Loan	Repayment	Interests	Annuity	Interest Rate
Year 0	35,313,145	959,972	2,118,789	3,078,761	6.00%
Year 1	34,353,173	1,017,571	2,061,190	3,078,761	6.00%
Year 2	33,335,603	1,078,625	2,000,136	3,078,761	6.00%
Year 3	32,256,978	1,143,342	1,935,419	3,078,761	6.00%
Year 4	31,113,636	1,211,943	1,866,818	3,078,761	6.00%
Year 5	29,901,693	1,284,659	1,794,102	3,078,761	6.00%
Year 6	28,617,033	1,361,739	1,717,022	3,078,761	6.00%
Year 7	27,255,295	1,443,443	1,635,318	3,078,761	6.00%
Year 8	25,811,851	1,530,050	1,548,711	3,078,761	6.00%
Year 9	24,281,801	1,621,853	1,456,908	3,078,761	6.00%
Year 10	22,659,949	1,719,164	1,359,597	3,078,761	6.00%
Year 11	20,940,785	1,822,314	1,256,447	3,078,761	6.00%
Year 12	19,118,471	1,931,653	1,147,108	3,078,761	6.00%
Year 13	17,186,818	2,047,552	1,031,209	3,078,761	6.00%
Year 14	15,139,266	2,170,405	908,356	3,078,761	6.00%
Year 15	12,968,861	2,300,629	778,132	3,078,761	6.00%
Year 16	10,668,232	2,438,667	640,094	3,078,761	6.00%
Year 17	8,229,565	2,584,987	493,774	3,078,761	6.00%
Year 18	5,644,578	2,740,086	338,675	3,078,761	6.00%
Year 19	2,904,491	2,904,491	174,269	3,078,761	6.00%
Year 20	0	3,078,761	0	3,078,761	6.00%

Year	0	1	2	3	4	5	6	7	8	9	10
Loan 0,9	35,313,145										
Equity 0,1	3,923,683										
Investment	-39,236,828										
Annuity		-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761
Operational Costs		-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572
Income from Operation		4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419
Income from Tairfs		2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868
Sum of Cash-Flows	**0**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**
Sum of Discounted Cash Flows	**0**	**54,242**	**51,659**	**49,199**	**46,856**	**44,625**	**42,500**	**40,476**	**38,549**	**36,713**	**34,965**

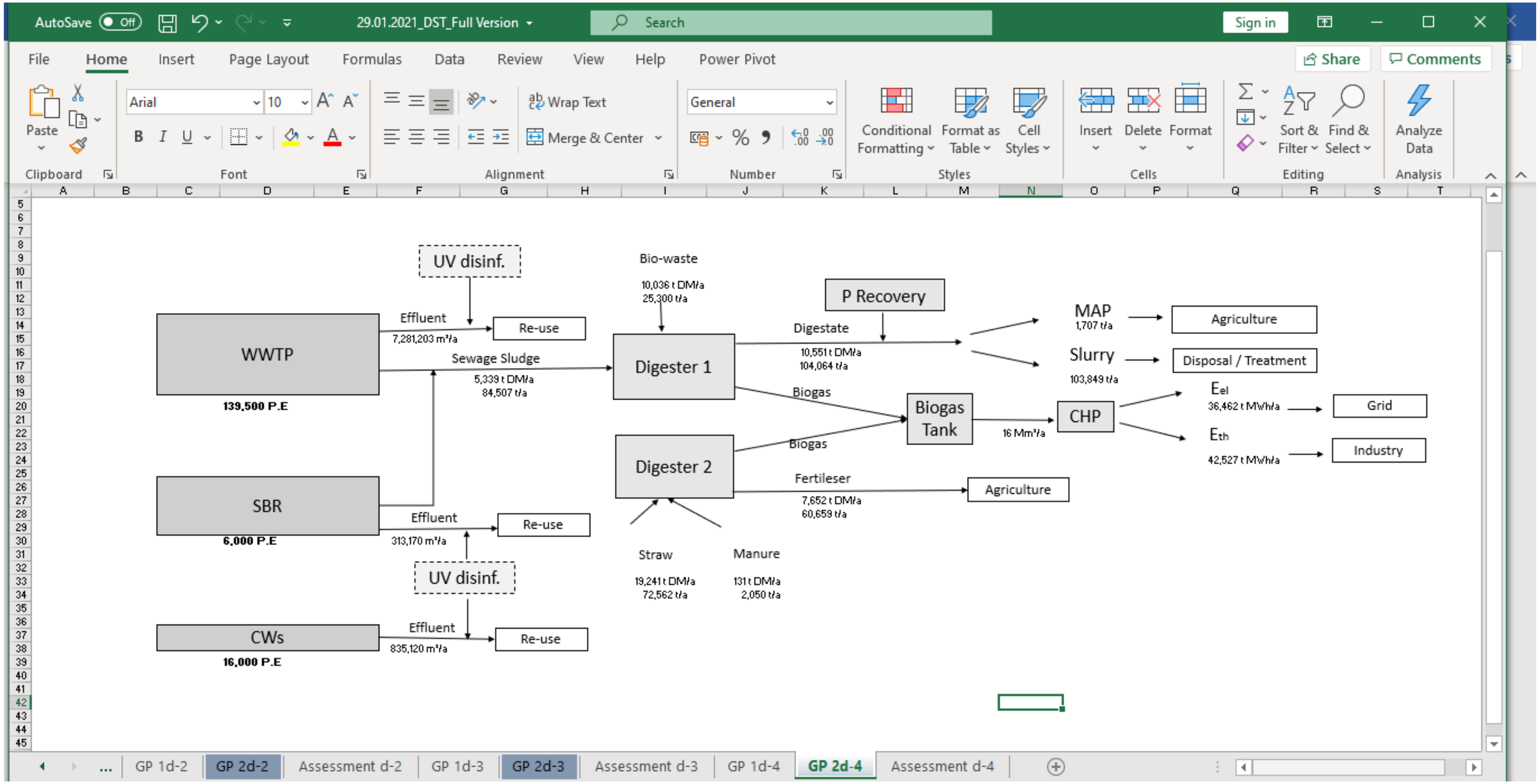
Year	11	12	13	14	15	16	17	18	19	20	1-20
Loan 0,9											
Equity 0,1											
Investment											
Annuity	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-3,078,761	-61,575,219
Operational Costs	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-3,692,572	-73,851,441
Income from Operation	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	4,677,419	93,548,374
Income from Tairfs	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	2,150,868	43,017,367
Sum of Cash-Flows	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**56,954**	**1,139,081**
Sum of Discounted Cash Flows	**33,300**	**31,714**	**30,204**	**28,766**	**27,396**	**26,091**	**24,849**	**23,666**	**22,539**	**21,465**	**709,773**

Column1	**Column2**
Discount Rate	**5%**

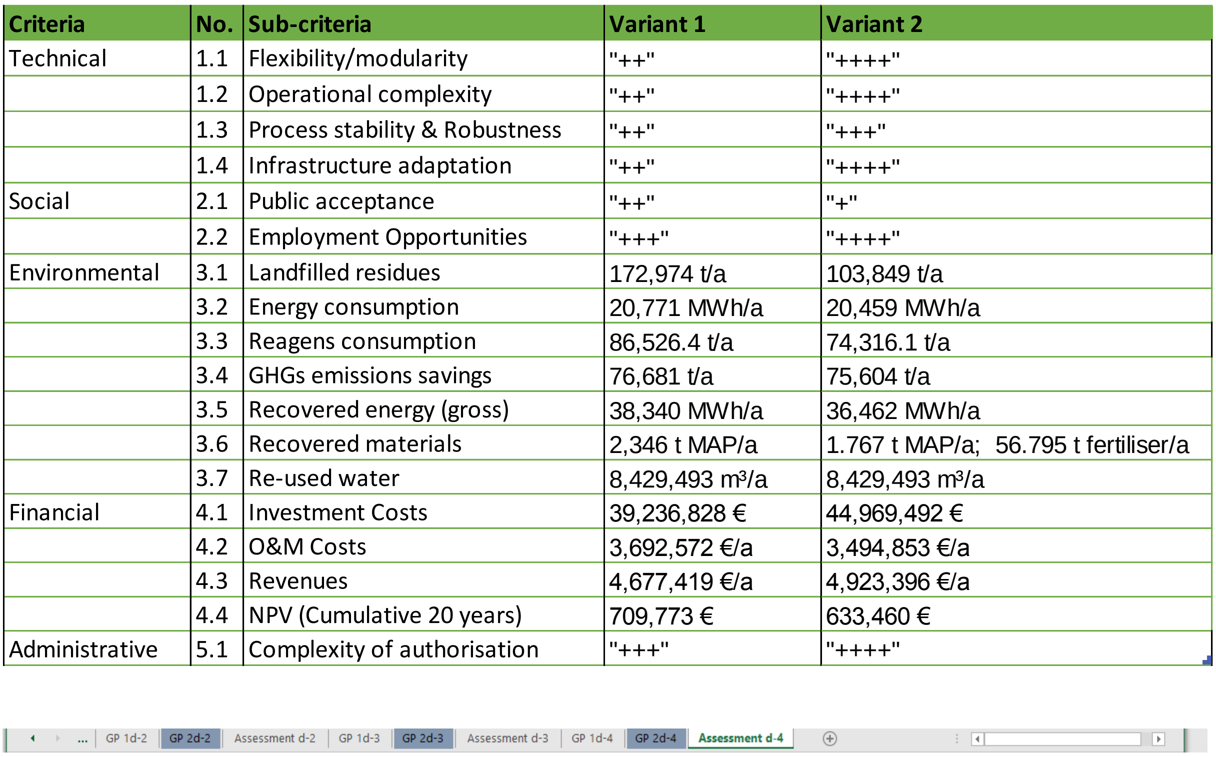
Column1	**Column2**
NPV	**709,773**


AutoSave Off
29.01.2021_DST_Full Version
Search
Sign in
File
Home
Insert
Page Layout
Formulas
Data
Review
View
Help
Power Pivot
Share
Comments
Paste
Clipboard
Arial
10
Font
Wrap Text
Merge & Center
Alignment
General
Number
Conditional Formatting
Format as Table
Cell Styles
Styles
Insert
Delete
Format
Cells
Sort & Filter
Find & Select
Editing
Analyze Data
Analysis
UV disinf.
Bio-waste
10,036 t DM/a
25,300 t/a
Effluent
8,429,493 m³/a
Re-use
P Recovery
MAP
2,346 t/a
Agriculture
WWTP
161,500 P.E
Sewage Sludge
5,978 t DM/a
93,312 t/a
Digester
Digestate
18,625 t DM/a
173,270 t/a
Slurry
172,974 t/a
Disposal / Treatment
Biogas
16 Mm³/a
CHP
Eel
38,340 t MWh/a
Grid
Eth
43,133 t MWh/a
Industry
Straw
19,241 t DM/a
72,562 t/a
Manure
131 t DM/a
2,051 t/a
GP 1d-2
GP 2d-2
Assessment d-2
GP 1d-3
GP 2d-3
Assessment d-3
GP 1d-4
GP 2d-4
Assessment d-4
Ready
80%
Type here to search
DEU
21:26
10/02/2021

***Appendix 6 – DST**, example of the Scenario d-4*



Appendix 6 – DST, *example of the Scenario d-4*



Criteria	No.	Sub-criteria	Variant 1	Variant 2
Technical	1.1	Flexibility/modularity	"++"	"++++"
	1.2	Operational complexity	"++"	"++++"
	1.3	Process stability & Robustness	"++"	"+++"
	1.4	Infrastructure adaptation	"++"	"++++"
Social	2.1	Public acceptance	"++"	"+"
	2.2	Employment Opportunities	"+++"	"++++"
Environmental	3.1	Landfilled residues	172,974 t/a	103,849 t/a
	3.2	Energy consumption	20,771 MWh/a	20,459 MWh/a
	3.3	Reagens consumption	86,526.4 t/a	74,316.1 t/a
	3.4	GHGs emissions savings	76,681 t/a	75,604 t/a
	3.5	Recovered energy (gross)	38,340 MWh/a	36,462 MWh/a
	3.6	Recovered materials	2,346 t MAP/a	1.767 t MAP/a; 56.795 t fertiliser/a
	3.7	Re-used water	8,429,493 m^3/a	8,429,493 m^3/a
Financial	4.1	Investment Costs	39,236,828 €	44,969,492 €
	4.2	O&M Costs	3,692,572 €/a	3,494,853 €/a
	4.3	Revenues	4,677,419 €/a	4,923,396 €/a
	4.4	NPV (Cumulative 20 years)	709,773 €	633,460 €
Administrative	5.1	Complexity of authorisation	"+++"	"++++"

Verzeichnis der in der Schriftenreihe „Stuttgarter Berichte zur Siedlungswasserwirtschaft“ seit 2008 erschienenen Veröffentlichungen

Band 192	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Zukunftsfähige Wasserversorgung – Von der lokalen zur globalen Herausforderung 22. Trinkwasserkolloquium am 14.02.2008 (2008) 116 S., 29 Abb., 4 Tab. (34,80 €)
Band 193	Hassan H. Shawly	Urban Water – Integrated Resource Planning to Meet Future Demand in Jeddah – Saudi Arabia (2008) 182 S., 38 Abb., 30 Tab. (34,80 €)
Band 194	Holger Kauffmann	Arsenelimination aus Grundwasser (2008) 151 S., 55 Abb., 22 Tab. (34,80 €)
Band 195	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Betrieb und Sanierung von Entwässerungssystemen 83. Siedlungswasserwirtschaftliches Kolloquium am 09.10.2008 (2008) 160 S., 45 Abb. 7 Tab. (34,80 €)
Band 196	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Von der Ressource bis zum Lebensmittel höchster Qualität 23. Trinkwasserkolloquium am 12.02.2009 (2009) 151 S., 59 Abb., 17 Tab. (34,80 €)
Band 197	Khaja Zillur Rahman	Treatment of arsenic containing artificial wastewater in different laboratory-scale constructed wetlands (2009) 184 S., 36 Abb., 10 Tab. (34,80 €)
Band 198	Juliane Gasse	Quantifizierung der Emissionen aus Abwasseranlagen und deren Auswirkungen auf die hygienische Qualität von Fließgewässern (2009) 220 S., 66 Abb., 77 Tab. (34,80 €)
Band 199	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Abwasserbewirtschaftung im Spannungsfeld politischer, klimatischer und technischer Entwicklungen 84. Siedlungswasserwirtschaftliches Kolloquium am 08.10.2009 (2009) 213 S., 56 Abb., 24 Tab. (34,80 €)
Band 200	Darla Nickel	Erfassung und Bewertung des Einflusses von gebietsstrukturellen Eigenschaften auf Trinkwasserpreise (2009) 174 S., 27 Abb., 43 Tab. (34,80 €)

Band 201	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Grundwasser und Grundwasserleiter – Nutzungskonflikte und Lösungsansätze 24. Trinkwasserkolloquium am 25.02.2010 (2010) 168 S., 81 Abb., 12 Tab. (34,80 €)
Band 202	Alexander Weidelener	Phosphorrückgewinnung aus kommunalem Klärschlamm als Magnesium-Ammonium-Phosphat (MAP) (2010) 165 S., 69 Abb., 15 Tab. (34,80 €)
Band 203	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Kanalsanierung – Werterhalt durch Wissensvorsprung 1. Stuttgarter Runde am 15.04.2010 (2010) 70 S., 26 Abb., 16 Tab. (24,80 €)
Band 204	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Regenwasserbehandlung in Abwasseranlagen – Prozesse und Lösungsansätze 85. Siedlungswasserwirtschaftliches Kolloquium am 14.10.2010 (2010) 213 S., 73 Abb., 11 Tab. (34,80 €)
Band 205	Fabio Chui Pressinotti	Anpassung der Tropfkörpertechnologie an heiße Klimazonen (2010) 196 S., 82 Abb., 22 Tab. (34,80 €)
Band 206	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Herausforderungen und Lösungen für die Wasserversorgung - Wettbewerb, Versorgungssicherheit, Innovation, Effizienzsteigerung 25. Trinkwasserkolloquium am 24.02.2011 (2011) 160 S., 47 Abb., 1 Tab. (34,80 €)
Band 207	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Kanalsanierung – Werterhalt durch Wissensvorsprung 2. Stuttgarter Runde am 14.04.2011 (2011) 80 S., 27 Abb., 1 Tab. (24,80 €)
Band 208	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Neue Verfahren und Betriebsstrategien in der Abwasserbehandlung 86. Siedlungswasserwirtschaftliches Kolloquium am 13.10.2011 (2011) 172 S., 71 Abb., 25 Tab. (34,80 €)
Band 209	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Wasserversorgung und Energie – Nutzungskonflikte; Management und Technik zur Optimierung der Energieeffizienz 26. Trinkwasserkolloquium am 16.02.2012 (2012) 156 S., 81 Abb., 15 Tab. (34,80 €)

Band 210	Geremew Sahilu Gebrie	Integrated Decision Support Tools for Rural Water Supply based on Ethiopian Case-Studies (2012) 310 S., 101 Abb., 110 Tab. (34,80 €)
Band 211	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Mikroschadstoffe und Nährstoffrückgewinnung – Praxiserfahrungen und Umsetzungspotenzial in der Abwasserreinigung 87. Siedlungswasserwirtschaftliches Kolloquium am 11.10.2012 (2012) 102 S., 44 Abb., 19 Tab. (34,80 €)
Band 212	Christian Johannes Locher	Anaerobe Behandlung von Abwasserkonzentraten aus der Halbstofferzeugung von Papierfabriken (2012), 206 S., 67 Abb., 40 Tab. (34,80 €)
Band 213	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Trinkwasserqualität und Gewässerschutz – Trinkwasserverordnung, Gewässerschutzkonzepte, Spurenstoffe 27. Trinkwasserkolloquium am 21.02.2013 (2013) 134 S., 77 Abb., 10 Tab. (34,80 €)
Band 214	Olaf Jerzy Kujawski	Entwicklung eines anlagenweiten Steuerungs- und Regelungskonzeptes für Biogasanlagen (2013) 238 S., 78 Abb., 35 Tab. (34,80 €)
Band 215	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Kanalsanierung – Werterhalt durch Wissensvorsprung 3. Stuttgarter Runde am 18.04.2013 (2013) 84 S., 109 Abb., 2 Tab. (24,80 €)
Band 216	Iosif Mariakakis	A two stage process for hydrogen and methane production by the fermentation of molasses (2013) 202S., 33 Abb., 34 Tab. (34,80 €)
Band 217	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Management des urbanen Wasserhaushalts – mehr als nur Kanalnetzplanung 88. Siedlungswasserwirtschaftliches Kolloquium am 10.10.2013 (2013) 178 S., 74 Abb., 18 Tab. (34,80 €)
Band 218	Özgül Demet Antakyali	An Evaluation of Integrated Wastewater and Solid Waste Management in Large Tourist Resorts (2013) 185 S., 71 Abb., 59 Tab. (34,80 €)
Band 219	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Zukünftige Herausforderungen für die Wasserversorgung – Vom Klimawandel über die Demografie bis hin zur Organisation 28. Trinkwasserkolloquium am 13.02.2014 (2014) 150 S., 45 Abb., 7 Tab. (34,80 €)

Band 220	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Kanalsanierung – Werterhalt durch Wissensvorsprung / Grundlagen, Konzepte und Innovation 4. Stuttgarter Runde am 10.04.2014 (2014) 108 S., 90 Abb. (24,80 €)
Band 221	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Energiepotenziale kommunaler Kläranlagen erkennen, nutzen und kritisch bewerten 89. Siedlungswasserwirtschaftliches Kolloquium am 09.10.2014 (2014) 146 S. 58 Abb., 11 Tab. (34,80 €)
Band 222	Kristy Peña Muñoz	Integrated sludge management concepts for green energy production in wastewater treatment plants in Heujotzingo City, Mexico (2014) 268 S., 34 Abb., 79 Tab. (34,80 €)
Band 223	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Zukunftsfähigkeit und Sicherheit der Wasserversorgung – Ressourcen / Tarife / Neue Technologien 29. Trinkwasserkolloquium am 26.02.2015 (2015) 132 S., 76 Abb., 32 Tab. (34,80 €)
Band 224	Timo Pittmann	Herstellung von Biokunststoffen aus Stoffströmen einer kommunalen Kläranlage (2015) 244 S., 54 Abb., 53 Tab. (34,80 €)
Band 225	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Wasser Schutz Mensch 5. Aqua Urbanica und 90. Siedlungswasserwirtschaftliches Kolloquium am 07. und 08.10.2015 (2015) 338 S., 147 Abb., 28 Tab. (34,80 €)
Band 226	Sebastian Tews	Aerob-biologische und oxidative Verfahren zur Behandlung von Membrankonzentraten aus der Holzstoff- und Altpapieraufbereitung (2015) 245 S., 62 Abb., 31 Tab. (34,80 €)
Band 227	Peace Korshiwor Amoatey	Leakage Management in the Urban Water Supply System of Ghana: Estimation and Detection Modeling (2015) 245 S.,67 Abb., 62 Tab. (34,80 €)
Band 228	Sebastian Platz	Charakterisierung, Abtrennung und Nachweis von Pulveraktivkohle in der Abwasserreinigung (2015) 256 S., 74 Abb., 51 Tab. (34,80 €)
Band 229	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	3 Jahrzehnte Trinkwasserkolloquium 3 Jahrzehnte Entwicklung in Wasserversorgung und Gewässerschutz 30. Trinkwasserkolloquium am 18.02.2016 (2016) 160 S., 78 Abb., 3 Tab. (34,80 €)

Band 230	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Stickstoffelimination auf kommunalen Kläranlagen im Spannungsfeld von Gewässerschutz, Energieeffizienzsteigerung und Industrieeinleitungen 91. Siedlungswasserwirtschaftliches Kolloquium am 13.10.2016 (2016) 132 S., 38 Abb., 15 Tab. (34,80 €)
Band 231	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Stand des Umwelt- und Arbeitsschutzes bei der Verchromung von Metall und Kunststoff Kolloquium zum integrierten industriellen Umwelt- und Arbeitsschutz am 30.11.2016 (2016) 126 S., 54 Abb., 9 Tab. (34,80 €)
Band 232	Mehari Goitom Haile	Accounting for Uncertainties in the Modelling of Emissions from Combined Sewer Overflow Structures (2016) 197 S., 93 Abb., 22 Tab. (34,80 €)
Band 233	Eduard Rott	Untersuchungen zur Elimination von Phosphor aus phosphonathaltigen Industrieabwässern (2016) 258 S., 57 Abb., 26 Tab. (34,80 €)
Band 234	Kenan Güney	Investigating Water Reusability in Cotton Processing Textile Dye-house by Applying Membrane Filtration (2017) 219 S., 64 Abb., 57 Tab. (34,80 €)
Band 235	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Risiken in der Wasserversorgung Vorsorge/Management/Minimierung/Kommunikation 31. Trinkwasserkolloquium am 06.04.2017 (2017) 132 S., 79 Abb., 6 Tab. (34,80 €)
Band 236	Pengfei Wang	Phosphorus recovery from wastewater via struvite crystallization in a fluidized bed reactor: Influence of operating parameters and reactor design on efficiency and product quality (2017) 202 S., 72 Abb., 20 Tab. (34,80 €)
Band 237	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Chemikalienmanagement und Umweltschutz in der textilen Kette Kolloquium zur nachhaltigen Textilproduktion am 21.09.2017 (2017) 174 S.,48 Abb., 9 Tab. (34,80 €)
Band 238	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Spurenstoffe im Regen- und Mischwasserabfluss Abwasserkolloquium 2017 am 26.10.2017 (2017) 130 S., 48 Abb., 13 Tab. (34,80 €)

Band 239	Marie Alexandra Launay	Organic micropollutants in urban wastewater systems during dry and wet weather – Occurence, spatio-temporal distribution and emissions to surface waters (2018) 240 S., 65 Abb., 38 Tab. (34,80 €)
Band 240	Asya Drenkova-Tuhtan	Phosphorus Elimination and Recovery from Wastewater with Reusable Nanocomposite Magnetic Particles (2018) 259 S., 78 Abb., 25 Tab. (34,80 €)
Band 241	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Integrated Best Available Wastewater Management in the Textile Industry Colloquium on Textile Wastewater Management 2018-09-19 (2018) 182 S., 99 Abb., 14 Tab. (34,80 €)
Band 242	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Spurenstoffe und antibiotikaresistente Bakterien – Schnittstelle Abwasserent- und Wasserversorgung Abwasserkolloquium 2018 am 08.11.2018 (2018) 118 S., 26 Abb., 8 Tab. (34,80 €)
Band 243	Karen Mouarkech	Combined energy and phosphorus recovery from black water, co-substrates and urine (2019) 296 S., 69 Abb., 107 Tab. (34,80 €)
Band 244	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Minimisation of Wastewater Emission from Textile Finishing Industries Colloquium on Textile Wastewater Management 2019-09-19 (2019) 148 S., 60 Abb., 20 Tab. (34,80 €)
Band 245	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Ansprüche an die Siedlungswasserwirtschaft – Kernaufgaben versus weitergehende Anforderungen Abwasserkolloquium 2019 am 10.10.2019 (2019) 143 S., 43 Abb., 2 Tab. (34,80 €)
Band 246	Siedlungswasserwirtschaftliches Kolloquium an der Universität Stuttgart	Sichere Trinkwasserversorgung trotz Klimawandel - wie resilient sind unsere Systeme und wo besteht Handlungsbedarf? 32. Trinkwasserkolloquium am 20.02.2020 (2020) 107 S., 52 Abb. http://dx.doi.org/10.18419/opus-10799
Band 247	Michael Seeger	Entwicklung und Validierung eines CSB-basierten und temperatursensitiven Bemessungsansatzes für Tropfkörper – Untersuchungen an technischen und halbtechnischen Tropfkörpern in warmen Klimazonen (2020) 308 S., 63 Abb., 46 Tab. http://dx.doi.org/10.18419/opus-10942

Band 248	Stephan Wasielewski	Ammoniumrückgewinnung aus Schlammwasser mittels Ionenaustausch an Klinoptilolith (2021) 273 S., 40 Abb., 52 Tab. http://dx.doi.org/10.18419/opus-11464
Band 249	Jovana Husemann	Development of a Decision Support Tool for Integrated Wastewater and Organic Material Flows Management in the Scope of Circular Economy (2021) 216 S., 52 Abb., 30 Tab.

Forschungs- und Entwicklungsinstitut für
Industrie- und Siedlungswasserwirtschaft
sowie Abfallwirtschaft e.V. (FEI)