Dissertation

Linking local energy and resource utilization in energy communities beyond traditional sector coupling

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Abstract

The sustainable development of the energy system requires the consideration of local resource use. This work includes the local resource utilization in the conventional coupling of energy sectors, especially in the form of waste and water. For this purpose, a model is developed to represent different sectors and consumers in order to cope with the complexity of this resource utilization. Model extensions describe business models for energy communities for improved local energy and resource use as well as investments in local resource treatment facilities. The introduction of indicators to quantify local sustainable development completes the methodology, which is applied in several case studies. The results show a high potential in energy recovery through resource treatment, although from a methodological point of view already a simplified modelling of sector coupling leads to high complexity and non-linear relationships in energy system modelling. The establishment of sustainable energy communities combined with stable business models leads to improvements in local energy and resource utilization. This also applies to investments in local resource treatment plants, although the high installation costs of such plants quickly reach their economic viability limits. Therefore, for local resource treatment strategies, the right choice of the individual system boundary of the catchment area is crucial for optimal system efficiency. The sustainability indicators introduced have proven to be a suitable measure for describing sustainable local development. Resulting guidelines for sustainability targets and funding instruments could further promote local sustainable development. Future research priorities for local resource utilization in sector coupling could lie in the expansion of the business models presented. This includes both the number of participants and the geographical extent of the area to be studied, as well as the time dimension with regard to a possible future expansion. Furthermore, the increased integration of hydrogen as an energy sector should be considered in extended analyses.

Kurzfassung

Die nachhaltige Entwicklung des Energiesystems erfordert die Berücksichtigung lokaler Ressourcennutzung. Diese Arbeit inkludiert die lokale Ressourcennutzung bei der konventionellen Sektorenkopplung, speziell in Form von Abfall und Wasser. Dazu wird ein Modell zur Abbildung verschiedener Sektoren und Konsumenten entwickelt, um der Komplexität dieser Ressourcenintegration gerecht zu werden. Modellerweiterungen beschreiben Geschäftsmodelle für Energiegemeinschaften für verbesserte lokale Energie- und Ressourcennutzung und Investitionen in lokale Behandlungsanlagen. Die Einführungen von Indikatoren zur Quantifizierung der lokalen nachhaltigen Entwicklung runden die Methodik ab, die in mehreren Fallstudien angewandt wird. Die Ergebnisse zeigen ein hohes Potenzial der Energierückgewinnung durch Ressourcenbehandlung, wobei methodisch bereits eine vereinfachte Abbildung der Sektorenkopplung zu hoher Komplexität und nichtlinearen Beziehungen in der Energiesystemmodellierung führt. Die Gründung nachhaltiger Energiegemeinschaften verbunden mit Geschäftsmodellen führen zu Verbesserungen lokaler Energie- und Ressourcennutzung. Dies gilt auch für Investitionen in lokale Behandlungsanlagen, wobei durch die hohen Installationskosten solcher schnell die Wirtschaftlichkeitsgrenzen erreicht werden. Deswegen ist bei lokalen Ressourcenbehandlungsstrategien die richtige Wahl der individuellen Systemgrenze des Einzugsgebietes für die optimale Systemeffizienz von entscheidender Bedeutung. Die eingeführten Nachhaltigkeitsindikatoren haben sich als geeignetes Maß zur Beschreibung der nachhaltigen lokalen Entwicklung herausgestellt. Daraus resultierende Richtlinien für Nachhaltigkeitsziele und Förderinstrumente könnten lokale nachhaltige Entwicklung weiter fördern. Zukünftige Forschungsschwerpunkte für lokale Ressourcennutzung in der Sektorkopplung könnten in der Erweiterung der vorgestellten Geschäftsmodelle liegen. Dies umfasst sowohl die Anzahl der Teilnehmer und die geographische Ausdehnung des zu untersuchenden Gebietes, als auch die zeitliche Dimension hinsichtlich einer möglichen zukünftigen Erweiterung. Außerdem sollte die vermehrte Einbindung von Wasserstoff als Energiesektor in erweiterten Analysen berücksichtigt werden.

Contents

Abbreviations

BaU	Business as usual
CEC	Citizen Energy Community
CHP	Combined heat and power
EC	Energy Community
EU	European Union
GeWoZu	Gemeinschaftlich Wohnen die Zukunft
GHG	Greenhousegas
KKT	Karush-Kuhn-Tucker
KPI	Key Performance Indicator
LSC	Local Sustainable Community
LSM	Local Sustainable Municipality
MILP	Mixed Integer Linear Program
MSW	Municipal solid waste
O&M	Operation and maintenance
OECD	Organization for Economic Co-operation and Development
P2P	Peer-to-peer
PV	Photovoltaic
REC	Renewable Energy Community
RED	Renewable Energy Directive
SC	Sustainable Community
SDG	Sustainable Development Goals
UN	United Nations
WFF	Willingness for water reduction flexibility
WFR	Willingness for waste reduction and recycling

1. Introduction

1.1. Motivation

Rising CO_2 emissions lead to all-time high global CO_2 emissions in 2022 (International Energy Agency, 2023). The increase is mainly caused by human actions, including the power, building and transport sectors, manufacturing, and overconsumption (United Nations, 2021). The emission of CO_2 in combination with other Greenhousegas (GHG) emissions, causes global warming by increasing the average temperature level by at least 1.5 °C. However, it is more likely that the global temperature will rise beyond this value, leading to extreme weather conditions in many regions (Intergovernmental Panel on Climate Change, 2023). Further counter effects can include drought, food insecurity and poverty (United Nations, 2021). Therefore, it should be aimed to limit the temperature increase to maximum 2 °C. However, to reach this target, net zero CO_2 emissions are mandatory (Intergovernmental Panel on Climate Change, 2023).

The implementation of such goals requires the cooperation of several nations. Early climate change mitigation actions in the Kyoto Protocol only considered GHG emission reductions for industrial countries. The Paris Agreement was established in December 2015, aiming to limit the global temperature increase to 2 °C and achieve net zero global CO_2 emissions by the middle of the century (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2022). Actions to reach the goals of the Paris Agreement are implemented in the European Green Deal. The deal provides an implementation to achieve climate neutrality by 2050 by including actions for energy, circular economy and mobility. Furthermore, the “Fit-for-55” package was established in the course of the European Green

Deal, which aims to reduce GHG emissions by 55 % by 2030 (compared to 1990 levels) (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2023).

Reaching the emission reduction targets of the "Fit-for-55" package requires decarbonization across emission-intensive sectors. The power sector can be decarbonized by increasing the share of renewable generation technologies across multiple energy sectors. Therefore, the European Commission introduced the Renewable Energy Directive (RED) in 2009, which became legally binding in 2021. The RED includes rules to promote investments and reduce costs for renewable energy generation technologies. Other significant aspects of the RED are energy efficiency and the transition towards a renewable, circular energy system that minimizes wasted energy (European Commission, 2023a). Incentives for renewable energy were further increased due to the Russian war of aggression on Ukraine, leading to the need for energy independence of Russia. The European Union (EU) introduced the "REPowerEU" incentive that considers further energy efficiency increase, accelerated renewable energy expansion and energy demand reductions. Transition paths include the doubling of Photovoltaic (PV) systems and heat pumps, aiming to reach a share of 45 % renewable energy by 2030 (European Commission, 2022a).

However, more than energy transition is required to fight all climate change challenges. Energy transition must be accompanied by sustainable development. According to the European Commission, 2023b, sustainable development is defined as *"Meeting the needs of the present whilst ensuring future generations can meet their own needs"*. Moreover, sustainable development is composed of three fundamental pillars, namely, environmental, economic and social pillars. Thus, sustainable development policies must address all three pillars simultaneously. The United Nations (UN) introduced a globally applicable set of rules for sustainable development: The United Nations Sustainable Development Goals (SDG) (United Nations, 2022). These include 17 goals and 169 targets that address fundamental actions for sustainable development. The goals consider energy and resource-related activities, but also social aspects. Therefore, the SDG can be consulted for reaching energy system climate neutrality while also ensuring resource efficiency.

The SDG 2030 agenda mainly addresses regional levels. These levels can promote peer learning and implement sustainable development at the local level (United Nations, 2023b). Thus, decentralization and integrated energy system planning can be vital for the increase of renewable energy generation technologies by offering cost-effectivity and energy reliability (European Commission, 2020b, Akinyele et al., 2014). Moreover, local energy efficiency incentives can decrease GHG and reduce the need for generation and grid capacity expansion (United States Environmental Protection Agency, 2022).

However, local energy system transition must be performed over multiple energy sectors, rather than only for the electricity sector. This is done by the implementation of sector coupling. Coordinated sector coupling can provide opportunities to decarbonize sectors, where GHG reductions are more difficult to achieve than in the electricity sector. Thus, sector coupling can lead to circular energy systems by deploying energy-efficient technologies and using local energy resources (European Commission, 2020a). Sector coupling considers three perspectives, including sectors like household and industry, technological solutions such as heat pumps or electric vehicles and infrastructure for sector interlinking. Sector coupling leads to demand flexibility and integration of renewable energy (Wietschel et al., 2018, Gea-Bermúdez et al., 2021).

Furthermore, local sector coupling approaches should not only consider energy but also resource utilization of water and Municipal solid waste (MSW) (European Commission, 2020a). MSW treatment has a high potential in sector coupling by using recovered energy from waste treatment processes, while wastewater has energy recovery potential by the treatment of sewage sludge (Dlamini et al., 2019, Peccia and Westerhoff, 2015). Resource treatment energy recovery can also be implemented locally, as local authorities are often responsible for local resource management and treatment processes (United States Environmental Protection Agency, 2022). However, not only energy recovery, but also efficient management and utilization of resources should be considered in local sustainable development. Resource reduction incentives by resource recycling, such as material recycling or greywater reuse, can be further utilized in local sector coupling approaches with resource utilization (Demirbas, 2011, Zavala et al., 2016).

Local energy and resource utilization requires cooperation with consumers. However, without further incentives, consumers might not sufficiently improve energy and resource efficiency in their operations. Therefore, concepts that promote sustainable behaviour are increasingly established. Energy Community (EC) concepts are one option that aims to promote efficient and sustainable energy generation and consumption by forming local communities. The EU introduces different business models for ECs, including Citizen Energy Community (CEC) models for electricity sharing and Renewable Energy Community (REC) models for geographically limited renewable energy sharing [1]. However, both concepts only consider business models for energy utilization. Sustainable Community (SC) concepts have a wider implementation and can also consider local resource utilization, such as water conservation and waste recycling (Institute for Sustainable Communities, 2022). According to the definition of Egan, 2004, *"Sustainable communities meet the diverse needs of existing and future residents, their children and other users, contribute to a high quality of life and provide opportunity and choice. They achieve this in ways that effectively use natural resources, enhance the environment, promote social cohesion and inclusion and strengthen economic prosperity"*.

Waste and water have a high potential for sectoral interaction with energy system operations (Maldet et al., 2022b). Furthermore, local energy markets can provide business models and promote decentral generation (Maldet et al., 2022a, Teotia and Bhakar, 2016). Sustainable energy system operation can be facilitated by local green investments (Sun et al., 2022), while benchmarking sustainable operations can further encourage performance improvement (Chung, 2011). Therefore, this thesis provides analyses of resource utilization in sector coupling, with a particular focus on local energy and resource utilization business models and investments. Moreover, it introduces indicators for sustainable development that can provide benchmarks for sustainability improvement. All investigations are performed with a developed optimization framework which is further extended in the course of the thesis for the

[1](*Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ L 328, 21.12.2018, p. 82–209* n.d., *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199.* N.d.)

particular analyses. Section 1.2 presents the research questions that are addressed by the studies in this work, and Section 1.3 provides an overview of the structure of the thesis.

1.2. Research Questions

This thesis aims to investigate the opportunities and impacts of local resource utilization in sector coupling. Four contributions address the objective, each associated with a particular research question. However, the analyses in the contributions can also provide results to other research questions than the associated ones. The contributions are based on four first-author publications in scientific journals (Maldet et al., 2022b, Maldet et al., 2023c, Maldet et al., 2023b, Maldet et al., 2023a). The first contribution provides an introduction to the core objective by giving an overview of the potential of waste and water utilization in sector coupling. Furthermore, it introduces the developed modeling framework that is used in the course of this thesis (Maldet et al., 2022b). The second contribution presents the application of local resource treatment business models, aiming to improve operational efficiency (Maldet et al., 2023c), while the third contribution focuses on local resource treatment investments that enhance the circular economy in the energy system (Maldet et al., 2023b). Finally, the fourth contribution shows the development of UN SDG indicators and applies these indicators in communities and municipalities to promote sustainable operations and investments (Maldet et al., 2023a). This section presents the research questions that address the core objective of this thesis.

Research Question 1. *How can resource utilization of waste and water be considered in sector-coupled energy systems, especially in communities?*

The first research question addresses the overall potential of waste and water utilization in sector coupling approaches. Waste and water have a high potential for integration in sector-coupled energy systems. The treatment of both resources can provide recovered energy to the system. Moreover, the efficient management of resources within the energy system is a fundamental aspect. However, the assessment of recovered energy implementation and resource management into sector-coupled energy systems with a variety of treatment options leads to a complexity increase in the whole system, which is outlined in the first contribution (Maldet et al., 2022b). Therefore, Research Question 1 focuses on the complexity and particularities of resource utilization into sector coupling. Furthermore, Research Question 1 addresses the local aspect of resource utilization. Resources arising in households must be managed and treated appropriately. Local resource treatment facilities can provide efficient resource utilization, but also other management options for consumers' resource management can be crucial. Therefore, Research Question 1 also focuses on resource utilization in communities, which is addressed in contributions two, three and four (Maldet et al., 2023c, Maldet et al., 2023b, Maldet et al., 2023a).

Research Question 2. *How can technology and business model implementation promote efficient energy and resource-related operations within a community?*

Local resource utilization in the energy system requires the involvement of consumers. However, without further encouragement, consumers are unlikely to seek higher efficiency in their local operations regarding energy and resources. Research Question 2 focuses on local technology introduction that can promote energy and resource efficiency. Moreover, business models for local resource utilization in the energy system can encourage consumers to achieve higher efficiency. Therefore, Research Question 2 addresses operational improvement by introducing local technologies and business models. Business models for community operation improvement are addressed in the second contribution (Maldet et al., 2023c), while business model extensions are analyzed in the third and fourth contribution (Maldet et al., 2023b, Maldet et al., 2023a). Local community establishments can strengthen the community spirit of consumers. Furthermore, technologies and business models can be provided for whole communities rather than single consumers. Thus, Research Question 2 provides a specific focus on community operation improvement.

Research Question 3. *How can investments in local resource treatment capacities improve municipal energy supply and circular economy?*

Apart from business models and technology operations, additional investments in local technologies can further promote resource utilization. These technologies can include local generation and storage capacities, as well as waste and sewage treatment facilities. Moreover, resource treatment can provide recovered energy to local communities, providing additional benefits through capacity investments. Therefore, Research Question 3 targets the improvement of a transition to a circular economy in the energy system by local capacity investments. Resource treatment and management are often the responsibility of local authorities. Municipalities can be responsible for providing such services to residents. Thus, Research Question 3 addresses local community formation at a higher level by community establishment over whole municipalities. The third contribution addresses the impact of business models on investments in local communities (Maldet et al., 2023b), while the fourth contribution applies investment decisions in context with community benchmarking (Maldet et al., 2023a).

Research Question 4. *How can energy- and resource-related UN SDG indicators be established and applied in communities and municipalities to promote efficient operations and technology utilizations?*

The previous research questions indirectly address local sustainable development, leading to contributions to the UN SDG. However, determining the contributions to the UN SDG is not applicable due to the lack of simple and applicable local UN SDG indicators. Therefore, Research Question 4 targets the development of local UN SDG indicators for communities and municipalities, putting a particular focus on the energy and resource-related UN SDG. However, the indicator development focuses on the simple applicability of the proposed indicators. Such UN SDG indicators can provide benchmarking to local communities, leading to potential operation efficiency improvements and local technology utilizations. Thus, Research Question 4 also focuses on community and municipality efficiency improvement by indicator establishment. The fourth contribution presents the development of such indicators and their application in local communities (Maldet et al., 2023a).

Figure 1.1 visualizes the interactions between the research questions. The four scientific contributions are considered for the elaboration of the research questions. Research Question 1 addresses the fundamental issues of resource utilization in sector coupling, while Research Question 2 directly applies the introduced concepts in community operational analyses. Furthermore, Research Question 3 extends the operational analyses of Research Question 2 to investment decisions and implements the basic issues of Research Question 1. Finally, Research Question 4 focuses on UN SDG indicator development and applies these indicators to community and municipality concepts of research questions 2 and 3. All of the research questions are addressed by the development and extension of an optmization framework, which is established in the course of this thesis.

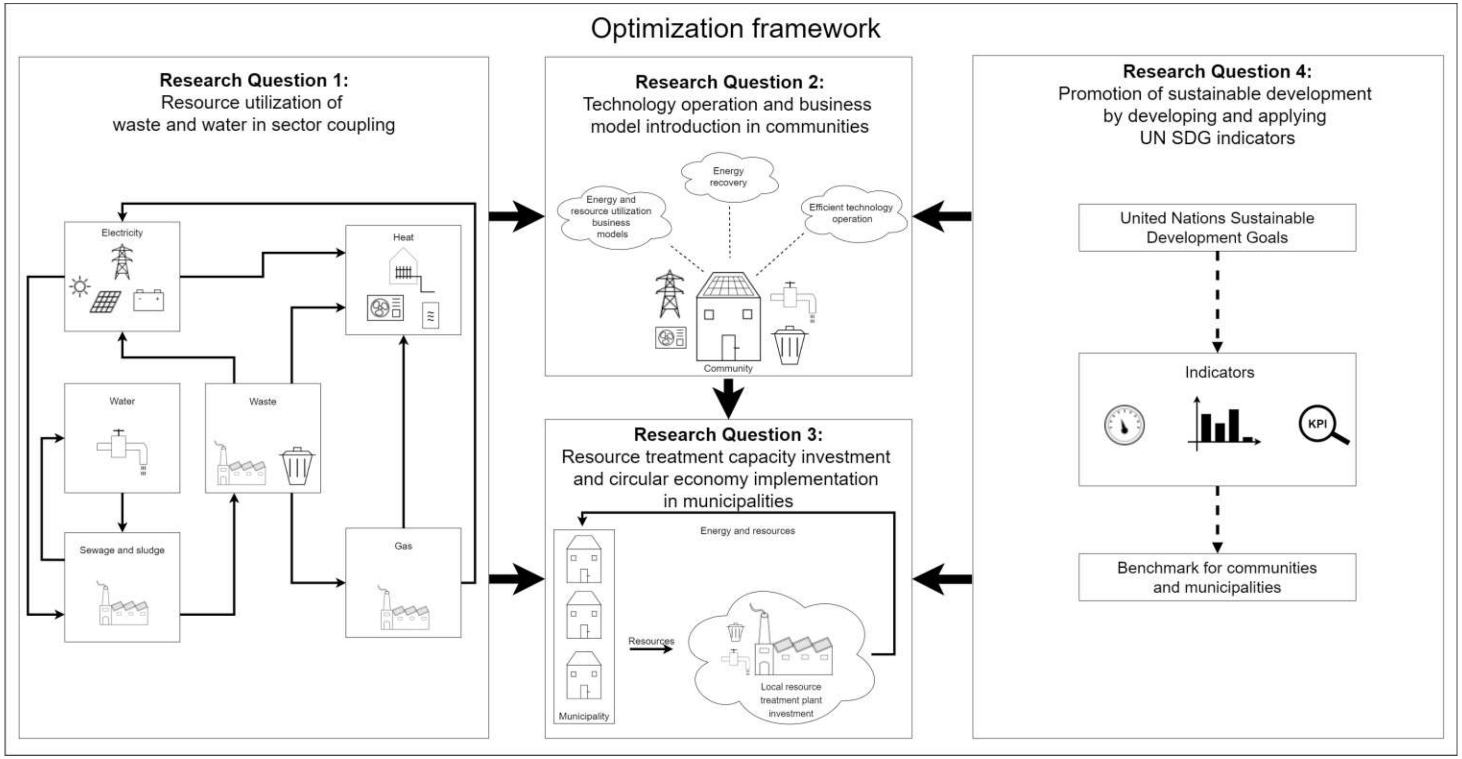

Figure 1.1.: Relation and implementation of the research questions based on the four contributions (Maldet et al., 2022b, Maldet et al., 2023c, Maldet et al., 2023b, Maldet et al., 2023a)

1.3. Structure of the thesis

The remaining thesis is structured as follows. Chapter 2 presents the state of the art and literature on the topics addressed in this thesis. It offers opportunities for resource utilization in sector coupling, including waste, water and greywater. Moreover, it focuses on integrating such in current sector coupling practices. Resource utilization in local communities is discussed by addressing business models, resource management methods and the impact of capacity investments. Moreover, Chapter 2 provides an overview of the literature on the quantification of the SDG, with a particular focus on sustainability indicators and benchmarking. Finally, Chapter 2 presents the novelties and progress beyond the state of the art in this thesis.

Chapter 3 presents the optimization framework, which is developed for addressing the research questions. It shows the model methodology and the test of the model in a testbed. Moreover, the chapter investigates the potential, relationships and complexity of resource utilization in sector coupling. Therefore, the testbed investigations provide contributions to Research Question 1. The chapter is based on Maldet et al. (2022b).

The analyses in Chapter 4 extend the modeling framework. This chapter presents the model extensions to multiple consumer operations and business model implementations. Therefore, it presents the method of the extended model and the business models. Furthermore, the chapter shows the framework application in a case study in a local community. Results in Chapter 4 present the impact of resource utilization business models and technology operation on improving community operation efficiency. Moreover, the chapter discusses service provision opportunities in communities and it discusses the benefits of local community establishment and business model introduction in context with local resource utilization. Thus, Chapter 4 contributes to Research Questions 1 and 2. Work in this chapter is based on Maldet et al. (2023c).

Chapter 5 further extends the modeling framework to capacity investment decisions for energy generation and storage technologies and resource treatment facilities. Thus, the chapter presents the framework extension methodology. Furthermore, the modeling framework is applied in a municipal case study, whereas Chapter 5 presents the workflow and configurations in the case study. Analyses in the chapter focus on the impact of local technology investments on energy system operation regarding resource utilization and circular economy. Furthermore, the results present the impact of different municipal strategies on assets and municipal operations. Finally, the chapter discusses the effects of municipal market scopes, energy and resource utilization and municipality goals based on the results. Therefore, this chapter significantly contributes to Research Question 3 and addresses Research Questions 1 and 2. Analyses in this chapter are based on Maldet et al. (2023b).

Chapter 6 presents the introduction and application of UN SDG indicators. Therefore, it provides a review of existing indicators. Based on these indicators, the chapter presents the development of new UN SDG indicators that are applied in local communities and municipalities. Furthermore, Chapter 6 presents the method and results of the community and municipality case studies, in which the indicators are applied. The results of the case studies focus on UN SDG indicators and the application of various policy paths, including target settings and different incentive schemes for sustainable development. Chapter 6 also discusses the applicability of the proposed UN SDG indicators and compares the introduced policy paths. This chapter mainly addresses Research Question 4. However, it also contributes to Research Questions 1, 2 and 3. Contributions are based on Maldet et al. (2023a).

Chapter 7 presents the synthesis of the results from the chapters 3, 4, 5 and 6. Therefore, this chapter discusses the findings concerning the research questions, presented in Section 1.2. Furthermore, Chapter 7 presents the opportunities, upscaling and transferability of the introduced concepts and results in terms of system perspective. Additionally, this chapter focuses on the potential strengths and limitations of the method.

Finally, Chapter 8 elaborates on the main conclusions of the thesis and the outlook on future prospects for research on local resource utilization in sector coupling.

2. State of the art and progress beyond

Sector coupling can provide new opportunities for smart operation and promote green transition while increasing the security of supply (Münster et al., 2020). Moreover, it can provide flexibility and decarbonization potential to the energy system (Ramsebner et al., 2021). Literature increasingly analyzes local resource utilization approaches as opportunities for sector coupling, because of the increasing relevance in the transition to a circular economy (Di Vaio et al., 2023). Furthermore, much research addresses the topic of circular economy regarding the UN SDG. This section presents existing work on local resource utilization in sector coupling, based on the literature reviews in the four scientific contributions (Maldet et al., 2022b, Maldet et al., 2023c, Maldet et al., 2023b, Maldet et al., 2023a).

Section 2.1 provides an overview of existing research on implementing resource treatment and utilization into sector coupling practices. Section 2.2 focuses on the increase of local resource utilization operation and improvement by resource treatment capacity investments. Section 2.3 particularly focuses on the UN SDG in context with benchmarking approaches for local implementation. Finally, Section 2.4 concludes the chapter with the novelties and progress beyond the state of research.

2.1. Resource utilization in sector coupling

This section presents resource utilization opportunities, with a particular focus on energy recovery (Section 2.1.1) and greywater utilization (Section

2.1.2). Moreover, it focuses on their potential implementation into sector coupling approaches in Section 2.1.3.

2.1.1. Waste, energy recovery and resource utilization

Apart from sustainable resource use, waste and water can have additional values in the circular economy through material and energy recovery, as presented by Tomić and Schneider (2022). Yaman et al. (2020) found that material recovery can lead to the highest CO_2 emission reductions. Both waste and water have a high potential for energy recovery. Various investigations, such as Thormark (2001), Moya et al. (2017), and Giugliano et al. (2011), have highlighted the potential of energy and material recovery from waste treatment. Treatment of resources for energy recovery can reduce waste quantities leading to positive environmental impacts, as stated by Zaharioiu et al. (2021). Dlamini et al. (2019) and Milutinović et al. (2017) described waste energy recovery processes, such as incineration and anaerobic digestion, as conversion technologies to prevent environmentally harmful landfilling. The results from Yi et al. (2018) and Chen (2018) have demonstrated that waste energy recovery may lead to increased CO_2 emissions, while Yaman et al. (2020) have outlined the potential for GHG reductions. Such contradictions highlight the complexity of energy recovery utilization, and show that the implementation of waste and sludge energy recovery depends on the considered energy system. Regarding water energy recovery, sewage sludge, as a by-product of sewage treatment, has a similar energy recovery potential to waste, as the resource can be incinerated or digested to biogas, as investigated by Peccia and Westerhoff (2015). Hong et al. (2009) have shown that sludge treatment could reduce the overall environmental impact of sludge, whereas Wang and Nakakubo (2021) have found that the energy recovery options are dependent on the design of the sewage treatment system. Furthermore, Singh et al. (2020) have found that sludge energy recovery has a positive impact on energy demand and land-use. However, the moisture content of sludge can lower the efficiency of sludge energy recovery, as reported by Quan et al. (2022). It must be considered that, as with waste treatment, sewage and sludge treatment leads to CO_2 emissions, as reported by Masuda et al. (2018). Not only can energy be recovered through sewage treatment, but also potable water, as mentioned by Verstraete et al. (2009). Moreover, Vu et al. (2022) highlighted the water recovery potential of sewage. As waste and sludge energy recovery is a widely considered topic, different real-life case studies have been set up in various publications. Amulen et al. (2022) have designed an energy recovery facility in Uganda, while Medina-Mijangos and Seguí-Amórtegui (2021) have analysed the economic impact of an energy recovery facility in Spain. The investigations in the mentioned literature have emphasised the importance of considering waste and sewage treatment in energy system analyses.

For an efficient treatment of waste and water, preliminary resource management are mandatory for resource utilization. Waste management should focus on prevention and operation, including the treatment and disposal of resources, as reported by Tseng et al. (2018). Zhang et al. (2022) have declared that future waste management developments should promote a transition from linear to circular management. However, according to Khan et al. (2022), successful waste management implementations are associated with challenges such as the improvement of waste collection. According to Corsten et al. (2013), waste management can contribute to CO_2 emission reductions, by implementing high-quality recycling and ensuring the energy efficiency of waste treatment processes. Water management concepts aim to treat water in all processes as a valuable and limited commodity. According to Sharafatmandrad and Mashizi (2021), the overall goal of water management is a sustainable balance between demand and resource availability. The investigations of Willis et al. (2010) and Zhang et al. (2018) have highlighted the importance of water management and conservation to address critical water issues regarding scarcity and sustainability. Aivazidou (2022) have introduced a potential water management framework, while Lee et al. (2022) have emphasised that such frameworks are dependent on national water policies. However, not only energy recovery implementation, but also resource utilization must be considered in holistic energy system analyses.

2.1.2. Greywater utilization

The efficient resource utilization of water can be achieved through the implementation of greywater, which is defined as wastewater from baths and laundry. Kitchen and toilet wastewater are excluded, due to their higher contamination (Department of Water and Environmental Regulation Government of Western Australia, 2022; Nolde, 2000; City of Golden, 2021). According to Sudarsan et al. (2021), greywater is becoming increasingly important, due to the depletion of natural water sources. Early concepts of Christova-Boal et al. (1996) and Al-Jayyousi (2003) in Australia and Jordan have identified greywater as an option for sustainable water use. The latter highlighted its potential in arid regions. A similar study has been carried out by Mandal et al. (2011) in India, where greywater has emerged as a feasible solution to overcome scarcity problems. Furthermore, Knutsson and Knutsson (2021) have developed a simulation model for water and energy saving which underlined the importance of greywater implementation. However, Khajvand et al. (2022) have found that greywater utilization is dependent on the status of greywater within national frameworks. Due to increasing water scarcity in many countries in the world, Santasmasas et al. (2013) have reported that potable water should only be used for purposes where the highest water quality is required. Couto et al. (2013) have carried out a study in a Brazilian airport, where the use of greywater was sufficient to cover non-potable water demands, highlighting the potable water saving potential. Furthermore, the studies of Zavala et al. (2016) and Zhang et al. (2021) have described rainwater harvesting as an additional opportunity to generate greywater. However, this is associated with uncertainty, due to a dependence on statistical rainfall data. Furthermore, rainwater harvesting is less cost-and energy-effective than greywater recycling, as found by Stang et al. (2021).

Greywater use has additional benefits, besides water saving. A further benefit of greywater use is a load reduction at sewage treatment plants, as reported by Ahmad and EL-Dessouky (2008). However, Radingoana et al. (2020) have also identified potential environmental and health risks if greywater is not used with caution. Anuja et al. (2021) have reported that greywater utilization is highly dependent on quality standards. A particular awareness of greywater as a resource is therefore required, as declared in the studies of Mourad et al. (2011) and Soong et al. (2021). However, according to Cureau and Ghisi (2019) and Al-Husseini et al. (2021), greywater is still the most viable strategy for water-saving and reduction of potable water consumption.

2.1.3. Sector coupling practices

To include waste and water energy recovery in the energy system, sector coupling concepts must be implemented. Much of the existing literature in the field already focuses on sector coupling, such as the study of Wietschel et al. (2018), in which general perspectives of technology use in sector coupling have been investigated. Fridgen et al. (2020) have described sector coupling as a purposeful interaction of energy sectors for increasing the flexibility of energy demand and supply. Brauner (2022) and Edtmayer et al. (2021) have emphasised that a further advantage of sector coupling is the effect of peak load shaving. Moreover, sector coupling implementations require the interaction of many different sectors and conversion technologies for efficient operations, according to Mokhtara et al. (2020) and Gea-Bermúdez et al. (2021).

Resource utilization and treatment play fundamental roles in sector coupling concepts. Waste can be integrated into the energy system in the form of energy recovery processes, such as incineration and anaerobic digestion (Moya et al., 2017; Dlamini et al., 2019; Milutinović et al., 2017). The implementation of waste in sector coupling has a direct effect on energy infrastructure planning, as reported by Arnaudo et al. (2021). However, Puttachai et al. (2021) have found that there is no consistent conclusion on the effect of waste-to-energy on other energy system operations yet. According to Ohnishi et al. (2018), waste utilization in the energy system is important for promoting the transition to low-carbon cities. Energy recovery from sewage treatment can also be integrated in sector coupling approaches. Schäfer et al. (2020) have investigated the impact of sewage treatment plant inclusion, and concluded that the water sector should be included in sector coupling, due to the energy recovery potential of sewage treatment. Furthermore, the energy demand of sewage treatment plants should be considered in this context, according to Mitsdoerffer (2017). Due to the variety of opportunities for sewage treatment implementation in sector coupling, Neugebauer et al. (2022) have provided an overview of the energy recovery potentials of sewage treatment plants. According to Michailos et al. (2021), the generated profits are dependent on the techno-economic environment. Wastewater can be coupled with the thermal energy supply, as stated by Lichtenwoehrer et al. (2021). Additional energy recovery from sewage treatment can be gained through sludge combustion and anaerobic digestion, as reported by Mills et al. (2014). Sayegh et al. (2021) and Ni et al. (2012) have identified further potential for heat recovery from sewage, while Sarkar et al. (2014) and Hadad et al. (2022) have found potential in using microturbines for sewage flow energy recovery. However, processes in other energy sectors require water as an additional input, which should also be considered in sector coupling, as reported by Nouri et al. (2019).

2.2. Implementing extended sector coupling in local communities

Besides general resource implementation into sector coupling, local resource utilization can enable further potential for a circular economy. However, local resource utilization requires the establishment of business models to encourage consumers to sustainable use of resources. Section 2.2.1 presents existing business models for resource utilization. Furthermore, local resource management is vital for a circular economy. Section 2.2.2 provides an overview of resource management practices, analyzed in the literature. Finally, Section 2.2.3 gives an overview of research focusing on local capacity investments, which are further required for increasing local resource utilization efficiency.

2.2.1. Business models for efficient community operation

Business models for local energy and resource utilization can be implemented in various forms. ECs provide business models for local energy generation and consumption and are a widely addressed topic in the EU due to the corresponding guidelines [1]. Reis et al. (2021) reviewed existing business models and found that energy generation, trading and consumption are crucial activities in EC business models. Hahnel et al. (2020) underlined that community prices strongly impact trading in an EC. Business models consider not only consumer involvement but also technology provisions in ECs, such as the work of Cielo et al. (2021). Franzoi et al. (2021) described ECs as an opportunity to improve PV self-consumption.

Furthermore, Sustainable Communities (SC) provide community models for sustainable development. According to Lu et al. (2017) SCs primarily aim to shift sustainability and contribution to the SDGs to the local level. The key success factors of SCs were identified by Morris et al. (2018) and these are government, experience, efficient management and sustainability. Santillan et al. (2022) developed a framework for community and infrastructure planning, providing important guiding principles. Energy implementation in SCs has a crucial role, but energy-related operations are not promoted by business models, as in ECs. However, as mentioned by Schoor and Scholtens (2015), energy in SCs also faces non-technological challenges. Schweizer-Ries (2008) showed that apart from technical problems, environmental psychological effects play a major role in achieving energy sustainability.

Community business models cannot only be established on the community level, but also on the municipal level. This concept can be similar to business models for sustainable cities. According to Battista et al. (2021), local administration should have more responsibility in energy action plans, while according to Bibri (2018), the establishment of a sustainable city has a high

[1] *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ L 328, 21.12.2018, p. 82–209* n.d.; *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199.* N.d.

complexity level, leading to the requirement of interdisciplinary design strategies. Thornbush et al. (2013) found that a combined mitigation-adaption method should be applied in sustainable city planning. Sperling et al. (2011) reviewed eleven municipal energy plans, finding the need for better coordination in planning strategies. Wretling et al. (2018) stated that the focus on municipal energy planning changed toward climate change mitigation. However, not all municipalities focus on this target. St. Denis and Parker (2009) found a policy that focuses on energy efficiency rather than renewable energy expansion. Brandoni and Polonara (2012) found that the coordinator has a fundamental role in municipal policy setting. However, Johannsen et al. (2021) stated that municipalities often lack the required planning tools for complex analyses. Moreover, Anastaselos et al. (2016) found that local solutions are dependent on consumer's needs and priorities.

2.2.2. Communal resource management practices

Resource utilization can have a fundamental role in sector coupling, as presented by Maldet et al. (2022b). Waste and water are highlighted to have a high potential in energy system operations. Waste and water management can be crucial for efficient resource utilization, as presented by Khan et al. (2022) and Aivazidou (2022). Namany et al. (2019) highlighted the importance of water management in the water-energy nexus. However, resource management of sludge as investigated by Ding et al. (2021) is not negligible in resource utilization either. Aside from management concepts, resource utilization considers resource sustainability according to the UN SDGs. Si et al. (2022) conducted a survey where they found that residents have strong intentions to save water and that policy incentives are required for further promotion.

Resource utilization can be applied in SCs. Gungor and Dincer (2021) and Babalola et al. (2022) investigated the integration of waste-to-energy recovery and the creation of a circular economy in SCs. Zsigraiová et al. (2009) outlined the need for efficient waste management in SCs. Water utilization is a fundamental aspect in SCs. Makropoulos and Butler (2010) investigated water supply and recycling technologies in SCs, with greywater implementation being considered as well. Moreover, Sapkota et al. (2015) highlighted the importance of greywater in their study on rainwater harvesting. Both infrastructure aspects and social aspects are essential for sustainable water utilization in SCs, as presented by Seyranian et al. (2015) and Otaki et al. (2017). Therefore, various business models also consider resource utilization. Geissdoerfer et al. (2018) established a framework for a comparison of circular business models, showing that business models have varying complexity. According to Lewandowski (2016), resource utilization business models can provide financial, social and environmental profits. The major goal of these business models is to generate value from resources kept in the loop, as stated by Urbinati et al. (2017). Ranta et al. (2018) found that cost efficiency is the key proponent of circular operation business models. According to Rizos et al. (2016), lack of supply and lack of capital are major barriers to business model implementation. However, as mentioned by Heyes et al. (2018), micro-sized businesses can play a significant role in the circular economy, once they are able to overcome these barriers.

2.2.3. Local capacity investments and technology utilization

Local energy and resource utilization requires technology investment. Wang and Davies (2018) highlighted green investment as an essential factor for sustainability in the supply chain. Sun et al. (2022) examined the role of fiscal decentralization in promoting green investment, with local governments reinforcing the environmental rules for innovations. Moreover, Liu et al. (2022) examined an emission reduction due to fiscal decentralization and renewable energy investment. Stakeholders must perform investments over multiple energy sectors. Alstone et al. (2015) found a need for innovative approaches to electricity access in decarbonized energy systems. Yazdanie et al. (2016) utilize local hydro, solar and waste resources in their study, leading to increased community self-sufficiency. Siraganyan et al. (2019) proposed more robust policies to promote renewable energy systems.

Aside from energy investments, municipalities must apply resource treatment and management practices. Kuznetsova et al. (2019) examined a trend to decentralized waste treatment plants, while Wang et al. (2021) found green investment as an important factor in influencing sustainability. Leigh and Lee (2019) examined that a transition from centralized water solutions to decentralized solutions like rainwater harvesting and greywater utilization can address urban challenges. Furthermore, Capodaglio et al. (2017) introduced new development paradigms that can promote local energy and material recovery. Therefore, Thiam (2011) found that support mechanisms could increase renewable energy deployment in remote areas. Chen (2021) stated that open information, integrated knowledge and responsibility are crucial for circular economy implementation. Reduction of waste and closing material cycles is vital, as stated by Mesjasz-Lech (2021). Thus, charging waste disposal costs should be done based on quantities, according to Alzamora and V. Barros (2020). However, Periathamby (2011) found that waste management structure is site-specific. Moya et al. (2017) compared different waste-to-energy technologies finding high opportunities to obtain commodities such as materials and energy. Milutinović et al. (2017) stated that anaerobic digestion is the best treatment practice from the environmental perspective. Moreover, Ohnishi et al. (2018) highlighted the importance of waste treatment in the transition to low-carbon cities. Therefore, Alam and Qiao (2020) analyzed waste treatment practices in a case study in Bangladesh, where they found high energy recovery potential from waste treatment. A similar study by Islam and Jashimuddin (2017) found cost-effectivity in waste energy recovery. Suthar and Singh (2015) examined further waste treatment energy recovery by compost biomass energy production. Furthermore, Zhang et al. (2010) investigated the environmental benefits of sludge reuse. Wang and Davies (2018) and Zhuang and Zhang (2015) found that waste management and water management can potentially help in community operations. Cureau and Ghisi (2019) found water uses such as greywater as an important alternative to reduce potable water demand. However, according to Piasecki (2019), financial incentives are required to promote alternative sewage systems.

2.3. Quantification and measuring of the UN SDG

Resource utilization business models can promote local sustainable development according to the UN SDG. However, measuring the contributions of such business models and investments requires indicators for the UN SDG. Section 2.3.1 introduces sustainability indicators, while Section 2.3.2 presents such application in benchmarking approaches. Moreover, Section 2.3.3 particularly focuses on indicators for the UN SDG.

2.3.1. Sustainability indicators

Sustainable investment, energy and resource management can contribute to sustainable development. Bortoluzzi et al. (2021) emphasized the role of multi-criteria decision processes in achieving sustainable development. However, indicators must be defined to measure sustainability. Drago and Gatto (2022) found that the establishment of policies is a crucial aspect of sustaining renewable energy. Gunnarsdottir et al. (2022) examined the need for robust indicators to develop sustainable policy goals. Ameen and Mourshed (2019) stated that sustainability assessment should be performed with the local context. Analyses from Evans et al. (2009) considered indicators, such as electricity price, GHG emission, energy and water consumption. Ngan et al. (2019) found significant indicators in public acceptance and economic performance improvement, while Ghenai et al. (2020) introduced environmental, economic, resource, technology and social as their five key indicators.

Not only sustainability but also energy and resource management should be assessed by indicators. Kylili et al. (2016) identified the KPI approach as the most valuable assessment tool. Razmjoo et al. (2019) performed an energy management assessment based on environmental impacts, renewable energy, energy access and policy. Moreover, Kourkoumpas et al. (2018) introduced simple and scalable indicators, including infrastructure energy and emission reductions. Bertoldi and Mosconi (2020) and Safarzadeh et al. (2020) further assessed energy policy indicators concerning energy-saving promotion. According to Bertanza et al. (2018), waste management indicators should consider characteristics of collected waste and environmental performance. Rodrigues et al. (2018) proposed considering social, economic and environmental indicators in waste management. Bezerra et al. (2022) stated that better coordination and problem identification are crucial for water management. Li et al. (2022) examined water management practices, with low water efficiency being the most significant factor in limiting sustainable water utilization. Special indicator systems can also be applied in communities and municipalities. According to Neves and Leal (2010), indicators should be used at the beginning of the planning process to assess the current situation. However, Klemm and Wiese (2022) found that not all sustainability indicators are applicable in urban energy systems. Moreover, Braulio-Gonzalo et al. (2015) found that sustainability concepts vary between regions.

2.3.2. Sustainability benchmarking

The concept of sustainability indicators can be extended to sustainability benchmarking programs by comparing consumers' sustainable development with sustainability indicators. According to Chung (2011), benchmarking might encourage poorly performing consumers to improve their performance. Moreover, Roth and Rajagopal (2018) stated that robust benchmarking programs might improve resource allocation for energy efficiency programs.

Dubey et al. (2017) emphasized that sustainability benchmarking is becoming increasingly crucial in industry. Moreover, Kılkış (2019) stated that decision-makers can use benchmarking results as a planning tool. Trigaux et al. (2021) developed benchmarking recommendations for the building sector with a transparent and user-friendly system being a significant aspect. Furthermore, Lazar and Chithra (2022) implemented benchmarking systems for worst and best building performances while Xuchao et al. (2010) developed a regression-based benchmarking model. Ding and Liu (2020) compared three benchmarking approaches, and they propose that policymakers should apply multiple benchmarking tools. Welling and Ryding (2021) identified life cycle assessment as an effective method for environmental impact measurement, while Hollberg et al. (2019) found that life cycle assessment-based benchmarks have been used as certification systems on the building level.

Many existing programs already implement benchmarking for technologies, communities or municipalities. These include the EU taxonomy for sustainability classification (European Commission, 2022b), the Austrian energy certificate as a building energy efficiency benchmarking tool (Bundesministerium für Finanzen, 2023) and the "e5" program in Austria, which supports municipalities in sustainable operation and rewards sustainable behaviour (e5 Österreich (2023)).

2.3.3. Quantification of the UN SDG

Bain et al. (2018) stated that most countries could generate estimates for SDG6 (clean water and sanitation), while SDG12 (responsible consumption and production) was less reported. Therefore, Razali et al. (2020) suggested fostering household waste separation behaviour, while Pujara et al. (2019) emphasized the importance of minimizing waste landfilling. Moreover, Santika et al. (2018) examined energy efficiency measures as an essential aspect of contributing to SDG7 (clean and affordable energy). According to Hák et al. (2016), indicators should consider policy relevance, link to the target and applicability. Therefore, Miola and Schiltz (2019) analyzed three different indicator methods, including mean evaluation, distance measure and progress determination. Swain and Yang-Wallentin (2020) introduce indicator equations to identify SDG contribution. Kubiszewski et al. (2022) applied linear regression to determine indicators, while Mischen et al. (2019) performed a community assessment to define indicators.

Even though much literature focuses on SDG quantification, the design of an SDG indicator system requires reference to widely applicable goals and norms. The UN SDG propose 17 goals with 169 practical actions to reach these goals (United Nations, 2022). The energy and resource-related goals are SDG6 (clean water and sanitation), SDG7 (clean and affordable energy), SDG11 (sustainable cities and communities), SDG12 (responsible consumption and production) and SDG13 (climate action). Moreover, SDG1 (no poverty) must be considered to keep the financial load on consumers at an acceptable level. The UN recognized regional economic integration in their 2030 agenda (United Nations, 2023b). They proposed that regional levels can provide valuable opportunities for peer learning. Moreover, the 2030 agenda focuses on the application of sustainable actions for each goal. However, the number of actions might result in high complexity in the application.

The ISO norm 37120 for sustainable cities and communities (ISO, 2018) introduces core indicators and supportive indicators to measure sustainable development. The norm categories energy, environment, finance, solid waste, wastewater and water and sanitation can be relevant for energy- and resource-related SDG. According to Moschen et al. (2019), ISO 37120 does not specify ideal actions for sustainable development regarding the UN SDG. Therefore, the norm should be seen as an additional sustainability indicator rather than a direct recommendation for sustainable development according to the UN SDG.

Furthermore, the Organization for Economic Co-operation and Development (OECD) proposes an action plan for countries to define actions leading to UN SDG contributions (OECD Council, 2016). Therefore, they introduce a set of targets for each UN SDG (OECD Council, 2017). However, the targets are defined for national policies and are therefore more suitable for national UN SDG indication. Jossin and Peters (2022) introduced an SDG indicator system that is applicable in municipalities. They raised 120 indicators, covering all SDGs. However, like for the UN SDG actions, the proposed actions by Jossin and Peters (2022) might lead to high complexity.

2.4. Novelty and contribution to the progress beyond the state of the art

The previous sections showed that much research focuses on sector coupling and local resource utilization. However, combining resource utilization with sector coupling approaches is barely investigated, especially on the local level. Therefore, this thesis provides novelties by performing research on local resource utilization in sector coupling, considering the impact on sustainable development. Therefore, the thesis introduces local business models and technology investments that promote resource employment and sustainable development. The novelties and contributions beyond the state of the art can be summarized as follows:

i **Inclusion of waste and water resource utilization and energy recovery technologies into a multiple-sector coupling approach**.

Much literature focuses on resource treatment energy recovery and resource sustainability. However, waste and water are yet to be considered in multiple-sector coupling approaches. Therefore, this thesis includes both resources in sector coupling. It considers energy and resource recovery of treatment processes. Moreover, it analyzes the interaction of resource utilization and treatment with other technologies and processes in the energy system. Several chapters in this thesis address the novelty of resource utilization in sector coupling. Chapter 3 provides general results on sector coupling, while chapters 4 and 5 address local resource utilization in communities and municipalities. Finally, Chapter 6 analyses the improvement of local resource utilization in sector coupling by establishing sustainability indicators.

ii **Introduction of local sustainable communities and municipalities to extend traditional energy communities by resource utilization**.

ECs are increasingly established in Austria for local energy generation and consumption. However, processes beyond energy are not considered in ECs. This thesis mainly focuses on local resource utilization. Therefore, it extends traditional ECs to local resource utilization models by forming local sustainable communities (at the household level) and municipalities (at the municipal level). Chapter 4 extends ECs at the community level, while Chapter 5 investigates extensions at the municipal level. Finally, Chapter 6 applies sustainability indicators to the newly introduced community and municipality concepts.

iii **Investigation of energy and resource-related technology and service provision business models across multiple sectors on the community level**.

Local resource utilization requires efficient operation of technologies and services. Moreover, local efficiency improvements require sustainable consumer behaviour. Existing work includes various options that enhance sustainable consumer behaviour. This thesis introduces new business models for energy and resource-related technology and service provision across multiple sectors. The business models aim to encourage consumers to efficient operations at the local level. Therefore, this thesis applies the business models in communities and municipalities. Chapter 4 mainly focuses on the application of different local energy and resource utilization business models. Therefore, the analyses consider establishing business models in communities, with a specific focus on operational improvement. Moreover, Chapter 5 applies several of the introduced business models in municipalities.

iv **Analysis of local energy generation and resource treatment capacity investment and localization in a municipality at different municipal strategies**.

Additionally to business models, investments in local technology capacity in the form of energy generation and treatment facilities can promote resource utilization. Much research already focus on local technology investment. However, the focus is mainly set on individual energy or resource-related investments. Therefore, this work performs local investment decision strategies, focusing on the localization of the technologies and facilities. Furthermore, it applies these analyses in a municipality, executing different municipal operations and development strategies. Chapter 5 mainly focuses on local investment decisions in municipalities. Therefore, studies in the chapter include investments in different municipal strategies, with a significant focus on circular economy and technology localization. Moreover, Chapter 6 performs capacity investment decisions in context with sustainability indicator application.

v **Development and application of a UN SDG indicator system that provides goals and benchmarks for efficient energy and resource utilization in communities and municipalities**.

> According to the UN SDG, sustainable development is a key aspect in local resource utilization. However, the contribution to particular SDGs can hardly be measured. Much research focuses on sustainability indicator development, where some work directly refers to the UN SDG. This work develops new UN SDG indicators for energy and resource-related SDGs that can emerge as potential benchmarks. Moreover, it applies the developed indicators in communities and municipalities and analyzes potential improvement in local sustainable development. Chapter 6 significantly focuses on the development and application of UN SDG indicators. Moreover, the chapter's analyses include investigations of sustainable development improvement by UN SDG indicator introduction, target setting and policy incentives.

This thesis addresses the research question by performing investigations with energy system optimization models that also consider the use of resources. Therefore, it introduces the development of a modeling framework for resource utilization in sector coupling. The framework is extended for particular analyses in the course of the thesis. Furthermore, the framework addresses the research questions and provides novelties and contributes to progress beyond the state of the art.

3. Optimization framework for local energy sector coupling with resource utilization

This chapter presents the method, fundamental functionalities and implementation of the Resource Utilization in Sector Coupling (RUTIS) framework (Maldet, 2022). Contributions of this chapter are based on Maldet et al. (2022b). Furthermore, it focuses on resource utilization in sector coupling and the resulting difficulties that might emerge.

Sector coupling is seen as a critical action for sustainability in energy systems, by reducing emissions in sectors that are more difficult to decarbonize. Sustainability can be achieved by decreasing the amount of wasted energy and resources in technological operations and through resource utilization. Such reductions are expected to lead to an overall increased energy system efficiency (European Commission, 2020a). Waste contributions to other energy sectors include incineration for electricity and heat generation, as well as anaerobic digestion for biogas generation (Kumar and Russel, 2000); however, the waste must be collected and processed for efficient use. The inclusion of water into the energy system can be considered from multiple perspectives. For many electricity generation processes, water is required as an additional input; for example, hydro power plants, cooling in thermal power plants, and electrolysis are processes requiring water. Furthermore, electricity is needed for water treatment processes, such as in sewage treatment plants (Hamiche et al., 2016). In addition, energy can be recovered from water treatment processes; for example, through the further processing of sewage sludge by combustion and anaerobic digestion (Oladejo et al., 2019). The recovery of water from sewage is another crucial aspect from the perspective of resource sustainability. However, the inclusion of waste and water in sector coupling leads to an increased level of complexity, which must be assessed. Therefore, this section puts a particular focus on the assessment of the resulting complexity.

For the elaboration of the research questions, a linear optimization modeling framework for resource utilization in sector coupling (RUTIS) (Maldet, 2022) is developed. The model optimizes the flows between the sectors based on minimum costs in hourly resolution while considering the interaction between different energy and resource sectors. The model is implemented in the open energy modelling framework (OEMOF) (Hilpert et al., 2018). OEMOF has proven to be the most suitable framework for the investigation due to the simple implementation of interactions between multiple sectors. Thus, the RUTIS modeling framework considers an extension and adaption of OEMOF[1].

This chapter presents the modeling framework with all its functionalities and mathematical equations in Section 3.1. Moreover, the Section presents the results on waste and water energy recovery potential and resource utilisation challenges in sector coupling in Section 3.2. Finally, a resumé in Section 3.3 concludes the framework introduction.

3.1. Model framework architecture and functionalities

The main goal of the modeling framework is a certain flexibility in order to make the framework applicable for all of the research questions. Therefore, the modeling framework architecture considers a modular implementation, where all technologies and functionalities are added to the optimization model as components. Depending on the technology, sectors are assigned to inputs and outputs of the technology. Moreover, as the elaboration of the research question requires the interaction between multiple consumers,

[1] The RUTIS model is implemented in Python and can be used by installing all required packages. Source and documentation of the model are found in: `https://gitlab.com/team-ensys/projects/maldet_energysystemmodel`

functionalities in the optimization model are assigned to specific consumers. With the model, it is possible to determine the contribution of resource treatment energy recovery to the overall inputs of the considered sectors. This is done by evaluation of the flows between the sectors by minimum costs in a dispatch optimisation. This section presents the detailed modeling workflow and the model equations.

3.1.1. Model workflow

The presentation of the workflow is fundamental to understand the functionality of the model. All steps required to determine the optimum flows are presented in this section. For the mathematical description of the model, the variables determined in the optimisation are defined using lower-case letters and pre-defined parameters with capital letters.

In the first step, the considered energy and service sectors must be defined. To connect the sectors, conversion technologies are required. Additionally, storage is implemented. For each sector, input and output sets are defined, with conversion technology flows allocated to these sets.

$$set^{in}_{sector} = \left\{x^{in}_{tech,1}, x^{in}_{tech,2}, ..., x^{in}_{tech,n}\right\}, \tag{3.1}$$

$$set^{out}_{sector} = \left\{x^{out}_{tech,1}, x^{out}_{tech,2}, ..., x^{out}_{tech,m}\right\}. \tag{3.2}$$

Sectors can also be interpreted as sets.

$$\mathcal{J} = \{Elec, Heat, Waste, Water, Sewage, Sludge, Greywater\}. \tag{3.3}$$

After the sectors and technologies are defined, the energy system is built up in the second step. This includes the conversion technology connections and the allocation of operational and purchase costs to technologies. After setting up the energy system, the optimization is performed by cost minimization. The results of the model are the dispatched flows between the sectors. An overview of the workflow is presented in Figure 3.1.

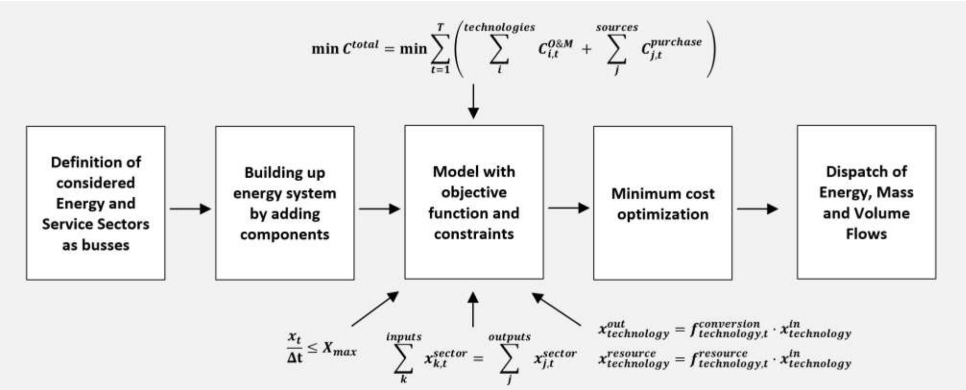

Figure 3.1.: Optimization Model Workflow.

3.1.2. Objective function

The objective of the optimization model is to determine the manner of operation of the energy system components which leads to the least total costs. The costs consist of conversion, storage, technological Operation and maintenance (O&M) costs, as well as the costs associated with external energy purchases from grids. For grids, there exists a difference between the modelled costs and real incurred costs. The model costs are set at a relatively high level, compared to the technology O&M costs. By using high model costs, the decentralized technologies are prioritised in the optimisation process. The real costs must be defined, in order to be able to reflect reality in the results. For evaluation of the incurred costs, real costs, in the form of procurement costs, are considered.

Conversion technologies can be summarised in sets, where each element has assigned O&M costs. The inputs and outputs of technologies are considered as sets, as some have multiple inputs or outputs. Furthermore, specific costs are assigned to each input and output. If no costs are incurred, the specific costs are set to zero.

$$\mathcal{T} = \{Heatpump, Battery, PV, ...\} \tag{3.4}$$

$$c_{i,t}^{O\&M} = \sum_{Inputs} C_{i,t}^{in} \cdot x_i^{in} + \sum_{Outputs} C_{i,t}^{out} \cdot x_i^{out} \quad \forall i \in \mathcal{T} \tag{3.5}$$

The sources can equivalently be summarised as sets:

$$\mathcal{E} = \{Electricitygrid, Gasgrid\} \tag{3.6}$$

$$c_{j,t}^{purchase} = C_{j,t}^{purchase} \cdot x_{j,t}^{purchase} \quad \forall j \in \mathcal{E} \tag{3.7}$$

The objective function minimizes the sum of technological O&M ($C_{technology}^{O\&M}$) and external purchase costs ($C_{source}^{purchase}$), which are incorporated into the total costs (C_{total}) (see Equation 3.8). Total costs are considered for the whole period T.

$$min(c^{total}) = min \sum_{t=1}^{T} (\sum_{i \in \mathcal{T}} c_{i,t}^{O\&M} + \sum_{j \in \mathcal{E}} c_{j,t}^{purchase}) \tag{3.8}$$

CO_2 emissions are considered as additional outputs of some technologies. For the conversion technologies of the set in Equation 3.4, local emissions are considered; whereas, for the source emissions in Equation 3.6, pre-chain emissions in generation and transmission steps are considered. To implement the CO_2 emissions in the model, the set of sectors in Equation 3.3 was extended with a CO_2 sector. Furthermore, the sets in Equations 3.1 and 3.2 were created for the CO_2 sector. The balance rule of Equation 3.23 was also applied to the CO_2 sector. However, the output flow set of the CO_2 sector only consists of one variable e_t^{total}, in which all of the CO_2 emission inputs are summed.

$$e_t^{total} = \sum_{i \in set_k^{in}} e_{i,t} \quad \forall k \in \mathcal{E}, k = Emissions \tag{3.9}$$

The CO_2 price is multiplied by the total emissions to obtain the total costs caused by the emissions:

$$c^{emissions} = \sum_{t=1}^{T} P^{CO_2} \cdot e_t^{total} \tag{3.10}$$

The emission costs are considered as additional costs in the objective function. Therefore, Equation 3.8 is extended using the emission costs, in order to take into account the influence of emissions in the optimisation, resulting in the adapted objective function:

$$min(c^{total,extended}) = min(c^{total} + c^{Emissions}) \tag{3.11}$$

3.1.3. Model constraints

The cost minimization is limited by model constraints. Due to the use of technology in the energy system, technological processing limitations are considered. The maximum energy that can be processed in each time step Δt is limited by the maximum power (P_i^{max}) of the technology. Similar limitations arise for maximum processed masses (V_i^{max}) and volumes (M_i^{max}), with maximum flows per time unit. The constraints are described in Equations 3.12–3.14.

$$\frac{q_{i,t}}{\Delta t} \leq P_i^{max} \quad \forall i \in \mathcal{T}, t \leq T \tag{3.12}$$

$$\frac{v_{i,t}}{\Delta t} \leq \frac{V_i^{max}}{\Delta t} \quad \forall i \in \mathcal{T}, t \leq T \tag{3.13}$$

$$\frac{m_{i,t}}{\Delta t} \leq \frac{M_i^{max}}{\Delta t} \quad \forall i \in \mathcal{T}, t \leq T \tag{3.14}$$

As storage is considered in the model, storage equations are also implemented as model constraints. Some storages, such as waste, are only emptied in certain time steps. For these technologies, disposal periods ($T^{disposal}$) are defined. Such disposal periods are combined together into a set ($Period^{disposal}$), with a number of elements equal to the disposal actions in the total time steps T. For all other time steps, no storage output is possible.

$$Period^{disposal} = \left\{T_1^{disposal}, T_2^{disposal}, ..., T_d^{disposal}\right\} \tag{3.15}$$

Each set element is calculated using the following equation.

$$T_d^{disposal} = \frac{T}{d \cdot T_{interval}^{disposal}} \tag{3.16}$$

The state of charge (SOC) for the storage equations is calculated using the SOC of the previous time step; the charge, discharge, and standby efficiencies (η); and the input and output decision variables. In the first time step, an initial value for the SOC is set.

$$soc_t = \eta^{sb} \cdot soc_{t-1} + \eta^{in} \cdot x_t^{in} - \frac{x_t^{out}}{\eta^{out}}, \tag{3.17}$$

$$soc_{t=0} = SOC^{start}, \tag{3.18}$$

$$soc_t = 0 \quad \forall t \in Period^{disposal}, \tag{3.19}$$

$$x_t^{out} = 0 \quad \forall t \notin Period^{disposal} \tag{3.20}$$

Furthermore, the conversion equations for each technology are implemented as model constraints through the technology conversion factor ($F^{conversion}$) in Equation 3.21. Depending on the technology, the conversion factor may also be time-dependent.

$$x_{i,t}^{out} = F_{i,t}^{conversion} \cdot x_{i,t}^{in} \quad \forall i \in \mathcal{T} \tag{3.21}$$

Some conversion technologies have additional required inputs from other sectors that are dependent on the primary input (Equation 3.22). Electrolysis, for example, requires water in a manner depending on the electricity input, in order to generate hydrogen. Such relations are implemented through additional constraints for technologies with at least two dependent inputs ($n_{inputs}^{technology}$).

$$x_{i,t}^{resource} = F_{i,t}^{resource} \cdot x_{i,t}^{in} \quad \forall i \in \mathcal{T}, n_{Inputs}^{technology} \geq 2 \tag{3.22}$$

Finally, a balance rule for all sectors, equating the inputs and outputs of sectors is implemented. The sets in equations 3.1 and 3.2, in addition to the sector set in Equation 3.3, are considered in this constraint.

$$\sum_{k \in set_k^{in}} x_{k,t} = \sum_{l \in set_k^{out}} x_{l,t} \quad \forall k \in \mathcal{E} \tag{3.23}$$

3.2. Model application: Testbed for energy- and resource sector coupling

The proposed modeling framework is applied to a testbed to test the model functionalities. Moreover, general relationships in energy sector coupling with waste and water are analyzed. This section provides an overview on the testbed configuration and on the model results for sector coupling, especially in the form of recovered energy.

3.2.1. Testbed configuration

To address the research questions, a testbed setup in a fictional city in Israel with a population of approximately 12000 was investigated. Israel is a suitable country for investigation of the research questions, as the decentralized energy generation in Israel is based, to a large extent, on gas (Ministry of Energy Department of Economics, 2018). As gas conversion technologies cause moderately high CO_2 emissions, investigation of the energy recovery potential in Israel is crucial. Furthermore, Israel is one of the countries with the highest level of water scarcity in the world, making investigations regarding water scarcity in Israel of utmost importance, according to Juanico and Salgot, 2022 and Wright, 2019. Figure 3.2 presents the configuration of investigated sectors and technologies in the testbed.

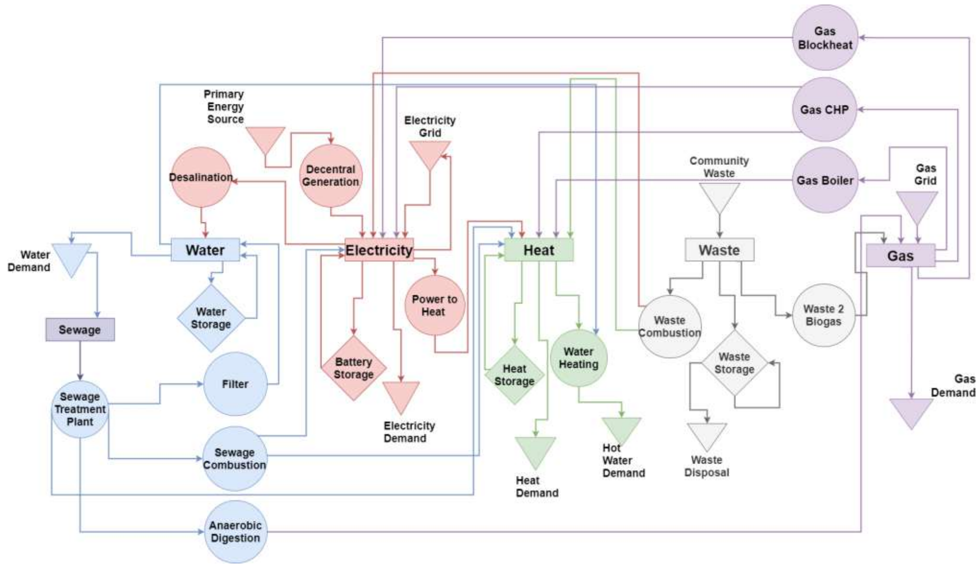

Figure 3.2.: Configuration of the testbed

The electricity sector considers procurement from the electricity grid and PV generation to cover the electricity demand. Heat is mainly procured from power to heat, in the form of heat pumps. Battery and heat storages are further included in these sectors. Gas technologies, such as blockheat generation, Combined heat and power (CHP) and gas boilers are further considered to cover the electricity and heat demand. Waste is considered in the sector-coupled system by MSW and its treatment options. These include waste incineration for energy recovery of electricity and heat and waste anaerobic digestion of biowaste for biogas generation. The water sector considers water procurement from desalination processes, that require electricity as input. Sewage is treated in sewage treatment plants, whereas treated, recovered water can be used for water demand coverage. Furthermore, sludge emerges as a by-product of sewage treatment. The sludge can be incinerated or digested to generate electricity, heat and biogas.

The execution of the examination was conducted in several steps. In the first step, the gas-based energy system in Figure 3.2 was set up using the RUTIS model. A major focus was placed on decentralized conversion technologies, which, in the first case study, consisted mainly of gas conversion and resource energy recovery technologies. All technologies, demands, and generation units in the setup were scaled and aggregated to the size of the considered city in Israel. In general, this setup represents the technology and resource utilization in the city. In the second step, the energy recovery potential of resource treatment in the setup was assessed. The method presented in Section 3.1 was applied for this assessment. Additionally, the change in technology use without resource treatment energy recovery implementation was determined. Investigations of the CO_2 emissions were further conducted in the second step. Based on this analysis, the inherent complexity of the processes was identified.

3.2.2. Results - implementation impact of resource treatment energy recovery

The results presented in this section include the results for energy recovery, with a particular focus on the relationships between energy recovery and other energy system operations.

Waste and water have non-negligible energy recovery potential, as they can provide high contributions to electricity and heat generation. The results with empty waste and sludge storage at the beginning of the year, in addition to the total costs, can be seen in Figure 3.3.

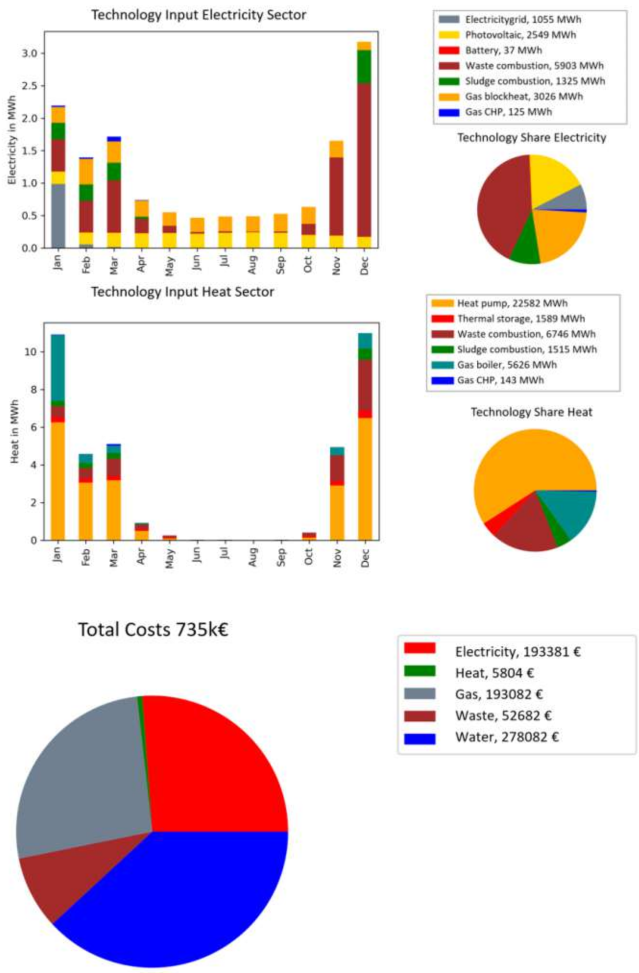

Figure 3.3.: Energy Recovery Contribution to Electricity and Heat

The contribution of waste combustion to electricity generation was 5903 MWh and the contribution of sludge combustion was 1325 MWh. Together, waste and sludge combustion can cover about 52 % of the electricity generation. For the heat sector, the total contribution was 8261 MWh (22 %). Gas, which is used at 22 % for electricity and 15 % for heat, can be covered by 79 % through sludge anaerobic digestion. The total waste is further treated for energy recovery, and less than 1 % of the sludge resources are disposed of without further restrictions. Regarding the costs, electricity and gas costs mainly emerged through grid purchasing, with costs between 158 k€ and 193 k€. Technological O&M costs were low, compared to grid procurement costs. The cost-intensive processing of sewage sludge is a special case, with costs of 170 k€. However, as its disposal without recovery of energy would also cause costs, sludge treatment is still the most efficient option. The overall costs of the gas-based setup for one year were 735 k€.

Moreover, waste and water inclusion into sector coupling results in a high level of complexity. Therefore, a sensitivity analysis on disposed waste and sludge was performed to assess the relationships between sectors and technologies in the sector-coupled system. Figure 3.4 shows the results for the gas-based setup. The disposed waste and sludge are displayed on the horizontal axis, whereas the value (in percentage) applies to both resources (e.g., 50% disposal means that 50% of waste and 50% of sludge are disposed of without energy recovery).

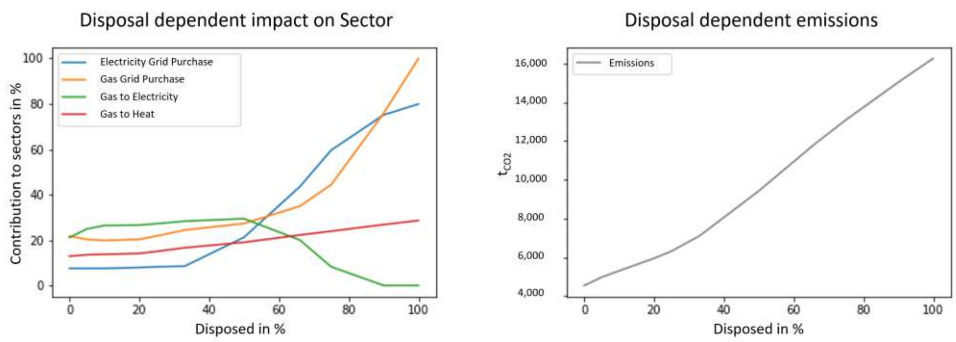

Figure 3.4.: Waste and sludge disposal sensitivity analysis

For the setup, the impacts of resource disposal on electricity grid purchase, gas grid purchase, and on gas technologies are presented. The values on the vertical axis describe the contribution of the technologies and grids to the respective energy sectors, in relation to the total contributions of all technologies (in percent). Furthermore, the impact on the CO_2 emissions is presented. Until a disposal of 35 %, the electricity grid consumption was constant, at about 8 %. Between 35 % and 90 % disposal, an increase in electricity grid consumption to 75 % emerged, due to lower electricity generation from waste and sludge combustion. The gas grid purchase steadily increased with increased disposal. At 75 % disposal, a sharp increase in gas grid consumption occurred, as not enough sludge can be utilized in anaerobic digestion to cover the gas demand. Regarding the gas technologies with electricity as output, a constant contribution until disposal of 50 % was identified. As less gas from anaerobic digestion was available at higher shares and the remaining gas was required for heat provision, the electricity generated by gas technologies decreased. With additional disposal, increasing gas conversion technologies for heat provision were required. Recovered heat from waste and sludge combustion could not be utilized, as the heat pumps were already operating at their capacity limits. Therefore, heat must be provided by gas technologies. The increased grid purchases and gas-to-heat technological operations led to increased CO_2 emissions with increased disposed waste and sludge. However, the complex relations in the gas-based setup lead to non-linearity between energy system technology operations and disposed waste and sludge.

For further analysis, a parameter describing the influence of energy recovery, $\Gamma_{component}^{recovery}$, was introduced, where the component in the index can be a specific energy system component. This parameter describes the impact of energy recovery on other energy system operations, with respect to the associated technologies. Thus, this parameter describes the relationships presented in Figure 3.4; however, this parameter is only introduced for theoretical discussion. In a linear relationship, this parameter only depends on the disposed waste and sludge.

$$\Gamma_{component}^{recovery} = f(m_{total}^{waste,disposed}, m_{total}^{sludge,disposed}) \tag{3.24}$$

In most energy system configurations, a more complex relationship than in

Equation 3.24 will occur. Such a relationship can be described with Equation 3.25:

$$\Gamma^{recovery}_{component} = f(m^{waste,disposed}_{total}, m^{sludge,disposed}_{total}, Q^{max}_{i}, \mathcal{T}, P^{CO_2}, ...) \quad (3.25)$$

For investigations on the energy recovery potential of waste and sludge in energy systems, such a relationship must be determined. If this relation is not available, a detailed simulation of the energy system, with consideration of all energy sectors, must be performed. However, regardless of the applied method, the potential assessment of energy recovery is coupled with a high level of complexity

3.3. Resumé

The results showed that waste and water energy recovery could make significant contributions to energy generation in energy sectors. Losses due to non-efficient treatment planning led to the conclusion that even though there is a lot of energy recovery potential in waste and water, associated implementations in real-life might be hindered due to failures in preliminary management, or in the treatment processes. In future energy system analyses, waste and water energy recovery should be considered, in order to increase overall energy efficiency. Therefore, waste and water should be implemented in sector coupling. Investigations on the energy recovery potential of waste and water in the energy system involve a high level of complexity. Options for the analysis include defining general relations for a considered energy system, or performing a detailed analysis of the energy system. However, due to the complexity of the connections, an energy system configuration-dependent analysis might be the more efficient method. However, resource utilization will have a major impact on energy system operations, as some resources, such as water, are becoming a valuable commodity. The disposal of resources without recycling or energy recovery might be declared as unsustainable, or even environmentally harmful. With the developed optimisation model, the impacts of energy recovery and emissions could be determined accordingly. The setup testbed could be appropriately processed, as the energy system operations were performed in the most efficient way. Through the model's modular design, the future extension to more conversion technologies and sectors, as well as its application in other energy system setups, can be carried out without high effort.

3.4. Nomenclature

Sets

Set^{in}_{sector}	Sector inputs	index: n
Set^{out}_{sector}	Sector outputs	index: m
$\mathcal{J}$	Set with all considered sectors	index: k
$\mathcal{T}$	Set with implemented technologies	index: i
$\mathcal{E}$	Set with implemented sources	index: j
$Period^{disposal}$	Set of all disposal time steps	index: d

Parameters

T	Total time steps	h
C^{in}_{t}	Technology input costs	€ per $[x^{in}]$
C^{out}_{t}	Technology output costs	€ per $[x^{out}$
$C^{purchase}_{t}$	Specific purchase costs	€ per $[x^{purchase}]$
P^{max}	Maximum power	kW
V^{max}	Maximum processed volume	m^3
M^{max}	Maximum processed mass	kg
Δt	Time step	h
$T^{disposal}_{interval}$	Disposal interval	h
$T^{disposal}$	Disposal time step	h
η^{sb}	Storage standby efficiency	/
η^{in}	Storage input efficiency	/
η^{out}	Storage output efficiency	/
SOC^{start}	State of charge at beginning	$[sector]$
$F^{conversion}_{t}$	Technology conversion factor	$[x^{out}/x^{in}]$
$F^{resource}_{t}$	Technology resource deployment	$[x^{resource}/x^{in}]$

P^{CO_2}	CO_2 price	€ per kg
$\Gamma^{recovery}_{component}$	Energy recovery relation	$[X^{technology}]/kg$

Decision Variables

$c_t^{O\&M}$	Operational technology costs	€
$c_t^{purchase}$	External purchase costs	€
c^{total}	Total costs	€
x_t^{in}	Input flow	Generic unit
x_t^{out}	Output flow	Generic unit
$x_t^{purchase}$	External purchased flow	$[sector]$
$x_t^{resource}$	Additional resource flow	$[sector]$
q_t	Energy flow	kWh
v_t	Volume flow	m^3
m_t	Mass flow	kg
soc_t	Storage state of charge	$[sector]$
e_t	Technology and source emissions	kg
e_t^{total}	Total emissions	kg
$c^{emissions}$	Total emissions costs	€
$c^{total,extended}$	Total costs including emissions	€

Table 3.1.: Model parameters and decision variables modeling framework

4. Business models for energy- and resource utilization in local sustainable communities (LSC)

This chapter presents the establishment of business models for efficient energy and resource-related operations. Therefore, it introduces a Local Sustainable Community (LSC). The analyses presented in this section particularly focus on resource utilization opportunities that emerge through LSC business models and providing community services. Methodology and results are presented based on Maldet et al. (2023c).

Local resource utilization in the energy system requires efficient operation of technologies and actions by consumers. However, financially oriented consumers might need more encouragement to perform efficient energy and resource-related operations. Thus, increasing efficient operations requires incentives, such as business models that encourage consumer behaviour. Moreover, the provision of specific technologies and services could provide operation efficiency increase. The establishment of communities could encourage consumers for more efficient behaviour, while community technologies and services could be provided for multiple consumers. Therefore, this section introduces energy and resource utilization business models in LSCs.

LSCs are a combination of EC concepts and SC concepts. An SC is defined as a union of people addressing multiple human needs together. Human encouragement and natural and financial capital are managed to meet these needs (Institute for Sustainable Communities, 2022; Egan, 2004). LSC concepts can include energy, resources and other commodities. However, the formation and implementation of an SC rely on the participants' incentives because financial benefits are lacking. Local ECs provide financial incentives and in these communities, energy is jointly generated and shared among the members. Even though the main objective in participation and formation should not be financial gain, cost savings can be generated by the provided incentives [1]. An LSC is a combination of both. In an LSC, energy and resources are jointly managed. Moreover, business models such as resource reduction agreements and service provisions are applied in the LSC, thus providing financial incentives for participation. These business models are applied to existing technologies and processes. Thus, no investment decisions are considered in LSC business models. Instead, the aim is to improve existing processes in energy sharing and resource treatment. An overview of the LSC concept is provided in Figure 4.1.

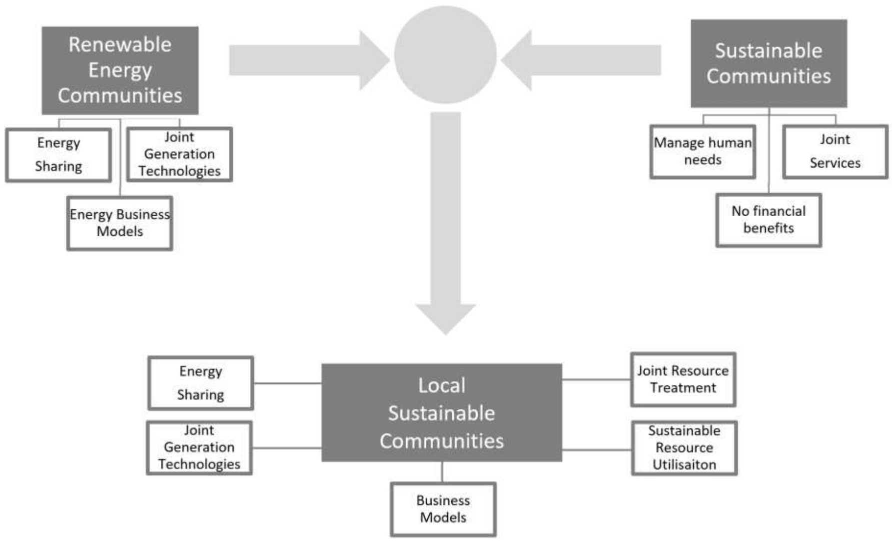

Figure 4.1.: LSC definition

A Mixed Integer Linear Program (MILP) of the considered LSC is established for the analyses. An optimization model on sector coupling in communities

[1](*Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ L 328, 21.12.2018, p. 82–209* n.d.; *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199.* N.d.)

with additional resource uitilization is developed in that context. Therefore, the RUTIS modeling framework, presented in Section 3 is extended to multiple consumers and business model implementation. The LSC potential is assessed by comparing the optimization results with and without LSC business models.

The core objective of the investigations is to analyze how the introduction of an LSC can encourage consumers to contribute to local, sustainable energy system operations. The introduction of LSCs should provide incentives for sustainable resource utilization. The impact assessment of services on LSC participants and service providers, also members of the LSC, is another core objective. This chapter provides an overview on methods for the RUTIS model extensions to LSC business models in Section 4.1. Furthermore, Section 4.2 presents the results on the impact of LSC formation, service implementation and resource markets. Section 4.3 discusses the significant results. Finally, Section 4.4 concludes the chapter with a resumé.

4.1. Methods

The method considers resource utilization in sector coupling for multiple consumers. Furthermore, the model functionalities include energy and resource business models. Therefore, the RUTIS model (Maldet, 2022) which was presented in Maldet et al. (2022b), was extended to trading and business model functionalities. This section presents the investigation setup, the method of the model and the case study.

4.1.1. Investigation setup

The optimization model is applied to the demo site Gemeinschaftlich Wohnen die Zukunft (GeWoZu) (Verein GeWoZu, 2020) in Waidhofen/Ybbs in Lower Austria. At this demo site, 33 people live together in 12 households in one building with the central goal of a sustainable lifestyle through community formation. The residents use joint technologies. Further implemented applications and technologies in the demo site are investigated by extending GeWoZu to an LSC to demonstrate the impact of LSC business models.

Specific consumers invest in their generation and conversion technologies, thus enabling energy sales to the community. Energy trading and resource reduction efforts are conducted. In the original setup, electric vehicles are owned by the residents; in the LSC extension a change is applied to community ownership and implementation of a carpool. Furthermore, joint resource treatment and resource energy recovery business models and resource business models for waste and water reduction are tested in the LSC.

The basic assumptions of the investigation and demand assumptions for the consumers are presented in the Appendix. Heating and cooling demand are evaluated for the whole house and are separated equally among the consumers. Transport demands vary depending on individual data. Changes in the configuration for specific analyses are explicitly discussed and presented in Table 4.1.

General model functionalities were presented by Maldet et al. (2022b). The proposed framework is extended to LSC operations and business models. The application of the framework in community investigations is presented in Figure 4.2.

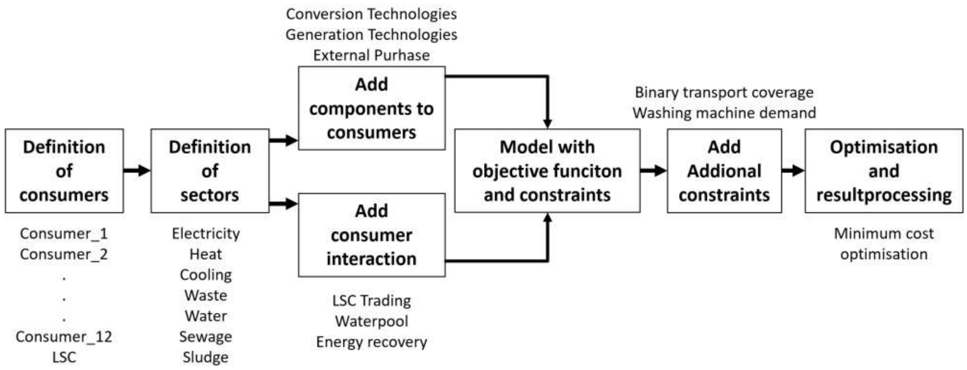

Figure 4.2.: Model Workflow

LSC model equations

First, the method of basic model functionalities is presented. The model objective is cost minimization within the LSC.

$$min(z) = min(c^{\text{tot}}) \tag{4.1}$$

The total costs without LSC consist of operational costs and procurement costs from external sources. These costs depend on technology-specific operational costs and predefined purchase prices of sources. Moreover, costs emerge due to the disposal of resources, which depend on specific disposal charges. Sets for consumers, external sources and technologies are defined in the same way as in the method presented in Maldet et al., 2022b.

$$c_{i,t}^{\text{tot,noLSC}} = \sum_{j \in \mathcal{S}} (\sum_{l \in \mathcal{T}} c_{i,j,l,t}^{\text{O\&M}} \quad + \sum_{(k \in \mathcal{E}} (c_{i,j,k,t}^{\text{purchase}} + c_{i,j,t}^{\text{disposal}})) \quad \forall i \in \mathcal{C} \tag{4.2}$$

$$c^{\text{tot,base}} = \sum_{t \in T} \sum_{i \in \mathcal{C}} c_{i,t}^{\text{tot,noLSC}} \tag{4.3}$$

$$c_{i,l,t}^{\text{O\&M}} = \sum_{Inputs} C_{l,t}^{\text{in}} \cdot x_{i,l,t}^{\text{in}} + \sum_{Outputs} C_{l,t}^{\text{out}} \cdot x_{i,l,t}^{\text{out}} \quad \forall i \in \mathcal{C}, l \in \mathcal{T} \tag{4.4}$$

$$c_{i,k,t}^{\text{purchase}} = \Pi_{k,t}^{\text{purchase}} \cdot x_{i,k,t}^{\text{purchase}} \quad \forall i \in \mathcal{C}, k \in \mathcal{E} \tag{4.5}$$

Consumers can feed excess electricity into the grid to generate revenues.

$$rev_{i,Elec,t}^{\text{feedin}} = \Pi_{Elec,t}^{\text{feedin}} \cdot x_{i,Elec,t}^{\text{feedin}} \quad \forall i \in \mathcal{C} \tag{4.6}$$

Basic model assumptions consider several constraints, which emerge due to technology limitations and input-output relations of conversion technologies.

$$x_{l,t} \leq X_l^{\max} \quad \forall l \in \mathcal{T} \tag{4.7}$$

$$x_{l,t}^{\text{out}} = F_{l,t}^{\text{conversion}} \cdot x_{l,t}^{\text{in}} \quad \forall l \in \mathcal{T} \tag{4.8}$$

Balance rules for each sector are fundamental constraints of the model and they define the demand coverage of predefined demands for each sector, as presented in Equation 4.9.

$$X_{i,j,t}^{\text{Demand,noLSC}} = \sum_{k \in \mathcal{E}} x_{i,j,k,t} + \sum_{l \in \mathcal{T}} x_{i,j,l,t} \quad \forall i \in \mathcal{C}, j \in \mathcal{S} \tag{4.9}$$

Introduction of the LSC operator

Furthermore, a new market player, which is referred to as LSC operator, is introduced. The LSC operator manages all relevant processes within the LSC, such as joint generation technologies, resource management and trading of energy and resources. Trading in the LSC is indirectly implemented via the LSC operator. The LSC operator can sell energy to generate revenue, and consumers can purchase energy from the LSC operator at predefined costs. This energy comes from LSC generation and conversion technologies, other consumers and recovered energy from resource treatment. Introducing an LSC operator reduces complexity because fewer trades between consumers must be modeled. Transactions take place indirectly via the LSC operator, thus reducing the number of model constraints. The implementation of an LSC operator is presented in Figure 4.3.

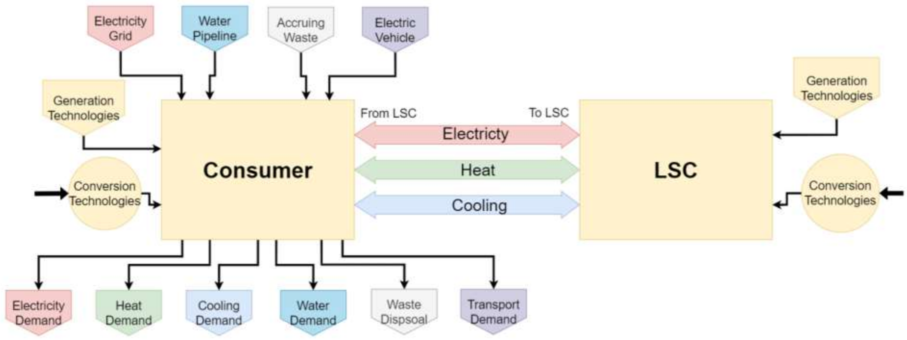

Figure 4.3.: Introduction LSC operator

The model methodology changes, as the balance rule for consumers is extended by LSC purchase and sale.

$$X_{i,j,t}^{\text{Demand,LSC}} = X_{i,j,t}^{\text{Demand,noLSC}} + x_{i,j,t}^{\text{LSC2cons}} - x_{i,j,t}^{\text{cons2LSC}} \tag{4.10}$$

The costs for the consumers are extended by LSC purchase costs and LSC sale revenues.

$$c_{i,j,t}^{\text{tot,LSC}} = c_{i,j,t}^{\text{tot,noLSC}} + x_{i,j,t}^{\text{LSC2cons}} \cdot \Pi_{i,j,t}^{\text{LSC2cons}} - x_{i,j,t}^{\text{cons2LSC}} \cdot \Pi_{i,j,t}^{\text{cons2LSC}} \tag{4.11}$$

The LSC has its own balance rule, which is implemented as an additional constraint. LSC inputs are generation and conversion technology outputs, in addition external procurement and recovered energy, respectively resources. Variables in the balance rule can be positive and negative, depending on whether they are sector inputs or outputs.

$$\sum_{k\in\mathcal{E}} x_{LSC,j,k,t} + \sum_{l\in\mathcal{T}} x_{LSC,j,l,t} + \sum_{i\in\mathcal{C}} x_{i,j,t}^{\text{cons2LSC}} = \sum_{i\in\mathcal{C}} x_{i,j,t}^{\text{LSC2cons}} \tag{4.12}$$

LSC costs consist of procurement costs, conversion technology operational costs and disposal costs. Costs for consumer purchases and revenues for consumer sales must also be considered.

$$c^{\text{own}}_{LSC,j,t} = \sum_{l \in \mathcal{T}} c^{\text{O\&M}}_{LSC,j,l,t} + \sum_{k \in \mathcal{E}} c^{\text{purchase}}_{LSC,j,k,t} + c^{\text{disposal}}_{LSC,j,t} \tag{4.13}$$

$$\begin{aligned} c^{\text{total}}_{LSC,j,t} = c^{\text{own}}_{LSC,j,t} &+ \sum_{i \in \mathcal{C}} x^{\text{cons2LSC}}_{i,j,t} \cdot \Pi^{\text{cons2LSC}}_{i,j,t} \\ &- \sum_{i \in \mathcal{C}} x^{\text{LSC2cons}}_{i,j,t} \cdot \Pi^{\text{LSC2cons}}_{i,j,t} \end{aligned} \tag{4.14}$$

LSC business models which, are introduced in the following sections, provide various options for consumer encouragement and energy-efficient community operations.

Energy sharing

The considered energy sectors in the LSC are electricity, heating and cooling. Consumers can sell energy and purchase energy from the LSC. Trading requires available grid infrastructure. Grid charges arise from grid provision by external service providers. Tariff and cost assumptions can be found in the Appendix. For electricity, the purchase tariff consists of energy costs, grid charges and additional fees.

$$\Pi^{\text{LSC2elec}}_{Elec,t} = \Pi^{\text{LSC2elec,energy}}_{Elec,t} + \Pi^{\text{grid}}_{Elec,t} + \Pi^{\text{surcharge}}_{Elec,t} \tag{4.15}$$

The energy price is dependent on LSC agreements. In the model, the price is assumed to be equal to the mean value of the electricity purchase tariff and feed-in tariff.

$$\Pi_{Elec,t}^{\text{LSC2elec,energy}} = \frac{\Pi_{Elec,t}^{\text{purchase}} + \Pi_{Elec,t}^{\text{feedin}}}{2} \tag{4.16}$$

No grid costs and surcharges are charged for the sale of electricity to the LSC. Therefore, the sale tariff is equal to the energy price.

$$\Pi_{Elec,t}^{\text{elec2LSC}} = \Pi_{Elec,t}^{\text{LSC2elec,energy}} \tag{4.17}$$

Costs for LSC purchase are revenues for the LSC operator and revenues for LSC sale are costs for the consumers. Only net costs are considered during the cost optimization. Grid charges and surcharges are considered external costs. Furthermore, in the electricity sector, combined metering and charging of power-based prices are assumed for all LSC members and the LSC operator. The maximum power within the considered time interval is evaluated.

$$p_{LSC}^{\text{max,elecgrid}} \geq \frac{\sum_{i \in \mathcal{C}} q_{i,Elec,elecgrid,t}^{\text{gridpurchase}} + q_{LSC,Elec,elecgrid,t}^{\text{gridpurchase}}}{\Delta t} \quad \forall t \in T \tag{4.18}$$

The maximum power is multiplied by a power-based price and the resultant costs are added to the total costs. The LSC operator pays power-based costs. Expense sharing depends on the LSC agreement.

$$c_{LSC,Elec}^{\text{power}} = p_{LSC}^{\text{max,elecgrid}} \cdot \Pi_{Elec}^{\text{power}} \tag{4.19}$$

Similar trading approaches are assumed for heating and cooling. Grid costs are charged when purchasing energy from the LSC, whereas trading within a building entails no costs. Prices are dependent on LSC agreements. The following set of equations describes the price assumptions for heating and cooling.

$$\Pi^{\text{LSC2energy}}_{j,t} = \Pi^{\text{LSC2energy,energy}}_{j,t} + \Pi^{\text{grid}}_{j,t} \quad \forall j \in Heat, Cool \tag{4.20}$$

$$\Pi^{\text{energy2LSC}}_{j,t} = \Pi^{\text{energy2LSC,energy}}_{j,t} \quad \forall j \in Heat, Cool \tag{4.21}$$

In addition to energy trading, resource utilization considerations are a key part of the LSC business model. The following section presents the models for waste and water.

4.1.2. LSC water model

Water is added in the LSC business models in the form of common sewage treatment within the LSC. Investigations that consider the water-energy nexus from the consumers' perspective are conducted. Demand coverage agreements to use water as a sustainable resource are made within the LSC. The following section describes both concepts.

Sewage treatment chain

Sewage $v^{\text{sewage}}_{LSC,t}$ as a share of the water demand $d^{\text{water}}_{i,t}$ emerging within the LSC is treated jointly. The treatment chain considers sewage treatment, recovered water $v^{\text{water}}_{LSC,t}$ and sludge $v^{\text{sludge}}_{t,LSC}$ as a by-product.

$$v^{\text{sewage}}_{LSC,t} = \sum_{i \in Consumers} Share^{\text{sewage}} \cdot d^{\text{water}}_{i,t} \tag{4.22}$$

$$v_{LSC,t}^{\text{water,LSC}} = K^{\text{waterrecovery}} \cdot v_{LSC,t}^{\text{sewage}} \tag{4.23}$$

$$v_{LSC,t}^{\text{sludge}} = \frac{Ct^{\text{sludge}}}{\rho^{\text{sludge}}} \cdot v_{LSC,t}^{\text{sewage}} \tag{4.24}$$

Sludge is stored and transported to treatment plants, where electricity and heat can be recovered by sludge incineration and untreated sludge is disposed.

$$q_{LSC,j,t}^{\text{sludgecomb}} = \eta_j^{\text{sludgecomb}} \cdot v_{LSC,t}^{\text{sludge}} \cdot H_S^{\text{sludge}} \quad \forall j \in Elec, Heat \tag{4.25}$$

The LSC operator provides all costs in the sewage treatment chain. Costs depend on operational costs and the amount of processed sewage and sludge. In the considered LSC, the treatment plant operators charge only the costs incurred for the treatment.

$$\begin{aligned} c_{LSC}^{\text{sewagechain}} = c^{\text{sewagetreat}} &+ c^{\text{storage,sludge}} + c^{\text{sludgetransport}} \\ &+ c^{\text{sludgecomb}} + c^{\text{sludgedisposal}} \end{aligned} \tag{4.26}$$

The required electricity for sewage treatment must be (virtually) provided by the LSC operator.

$$q_{LSC,t}^{\text{sewagetreat,elec}} = K^{\text{sewagetreat,Elec}} \cdot v_{LSC,t}^{\text{sewage}} \tag{4.27}$$

In return, the recovered energy is assigned to the LSC operator on the balance sheet. The LSC operator can then sell the recovered energy to generate revenues.

Water demand coverage

The LSC members agree to reduce their total water demand $d_{i,t}^{\text{water}}$. These agreements include a limitation of water purchase options. The different water coverage options are presented in Equation 4.28.

$$d_{i,t}^{\text{water}} = v_{i,t}^{\text{pipe,limited}} + v_{i,t}^{\text{water,LSC}} + v_{i,t}^{\text{poolpurchase}} + v_{i,t}^{\text{pipe,excess}} \tag{4.28}$$

Conventional water purchase $v_{i,t}^{\text{pipe,limited}}$ is limited to half of the predefined total water demand $D_{i,t}^{\text{water}}$. For limited pipeline purchase, conventional water prices $\Pi^{\text{pipe,water}}$ are charged. Another option is to purchase water from the LSC operator ($v_{i,t}^{\text{water,LSC}}$) in the form of recovered sewage. The water price is assumed to be only three-quarters of the conventional water price. However, LSC water purchase is limited to sewage treatment plant water recovery.

The third option for water procurement is virtual LSC water pool purchase $v_{i,t}^{\text{poolpurchase}}$ at half of the conventional water pipeline costs. This water pool is implemented as virtual storage. LSC members can reduce their predefined water demand to feed water into the pool and generate revenue based on a feed-in tariff $\Pi^{\text{waterpool}}$.

$$d_{i,t}^{\text{water}} = D_{i,t}^{\text{water}} - v_{i,t}^{\text{water2pool}} \tag{4.29}$$

Water reduction is limited by consumers' incentives. The limitation is implemented by a limiting factor K_{WFF}, representing a Willingness for water reduction flexibility (WFF).

$$d_{i,t}^{\text{water}} \geq D_{i,t}^{\text{water}} \cdot (1 - K_{WFF}), \quad K_{WFF} \in [0, 0.5] \tag{4.30}$$

The factor is either predefined or implemented stochastically, based on a water reduction survey conducted by Beaumias et al. (2009). The probability is an input for a random generator. It is determined by regression analysis of the data and is presented in Equation 4.31.

$$Prob_{WFF} = 0.4 \cdot e^{-6.2 \cdot K_{WFF}} \tag{4.31}$$

The final option for water purchase is excess purchase. Twice the conventional procurement costs are charged for these purchases. The total water demand is reduced by implementing limited water purchase and the introduction of water pool purchase are implemented as business models.

4.1.3. LSC waste model

LSC business models aim to use waste as a valuable resource. This section introduces waste energy recovery models and reduction models. A crucial consideration is that waste treatment and market models are applied only within the system boundaries of the LSC.

Waste treatment chain

The waste treatment chain is implemented equivalent to the sludge treatment chain. All incurred costs are paid by the LSC operator, whereas the recovered energy is assigned to the LSC on the balance sheet. The waste treatment chain is presented in Figure 4.4.

The LSC operator needs to shoulder costs for transport and treatment processes.

$$c_{LSC}^{wastechain} = c^{wastetransport} + c^{wastecomb} + c^{wastedisposal} \tag{4.32}$$

The recovered energy is equivalent to Equation 4.25. The only difference is that waste is incinerated instead of sludge.

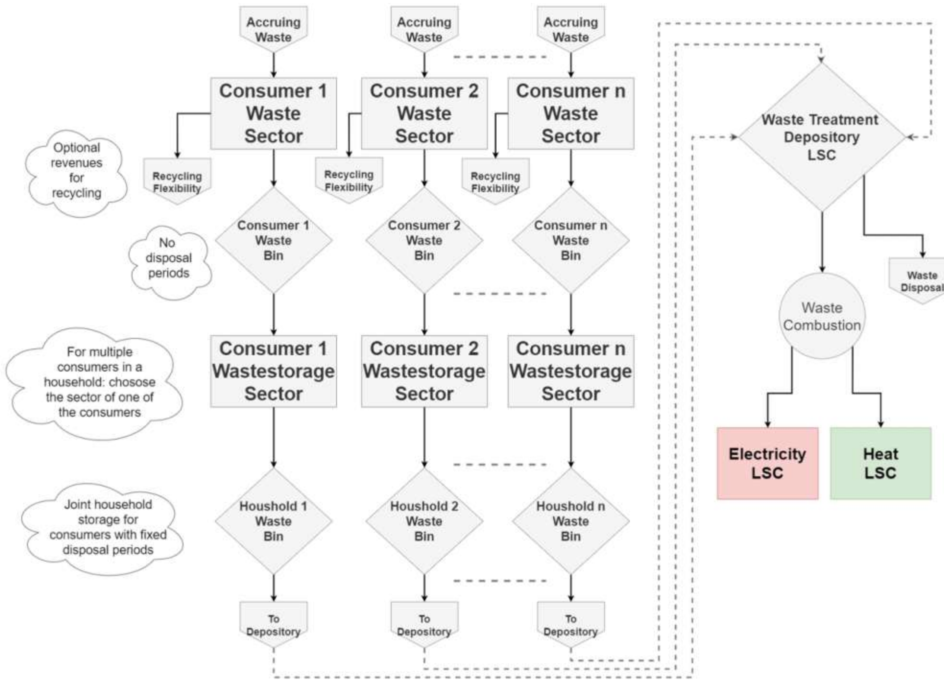

Figure 4.4.: Waste treatment Chain

Waste market price setting

The implementation of a waste market constitutes a significant portion of the LSC business model. Consumers can reduce waste and generate revenue through the sale on a market or policy funding. The maximally reduced waste amount is either predefined or stochastically (Equation 4.33) determined based on the survey of FOCUS Marketing Research (2022). It is described by the Willingness for waste reduction and recycling (WFR) K_{WFR}.

$$Prob_{WFR} = -1.1 \cdot K_{WFR}^3 + 8.2 \cdot K_{WFR}^2 + 0.4 \cdot K_{WFR} + 0.05 \qquad (4.33)$$

The recycled waste is limited by the product of the WFR and the total consumers' waste demand $D_{i,t}^{\text{waste}}$.

$$m_{i,t}^{\text{recycled}} \leq K_{WFR} \cdot D_{i,t}^{\text{waste}}, \quad K_{WFR} \in [0, 0.4] \tag{4.34}$$

Revenue from recycling depends on the amount of recycled waste and the defined waste market price $\Pi^{\text{wastemarket}}$. The waste market competes with savings from waste energy recovery. Appropriate market prices are elaborated by creating an equilibrium model of waste treatment cost savings and recycling revenues. Solving the equilibrium model enables the waste market price to be calculated by using Equation 4.35. This equation considers the usable recovered energy $\eta_{usable}^{\text{wastecomb}}$, waste heating value H^{waste}, combustion efficiencies $\eta_j^{\text{wastecomb}}$, operational costs of heat pump and waste combustion, electricity grid purchase costs $C_{Elec,grid}^{\text{purchase}}$ and the coefficient of performance of the heat pump $COP_{heatpump}^{\text{mean}}$.

$$\begin{aligned}\Pi^{\text{wastemarket}} = \eta_{usable}^{\text{wastecomb}} \cdot H^{\text{waste}} \cdot (\eta_{Elec}^{\text{wastecomb}} \cdot C_{Elec,Grid}^{\text{purchase}} \\ + \frac{\eta_{Heat}^{\text{wastecomb}}}{COP_{heatpump}^{\text{mean}}} \cdot C_{Elec,Grid}^{\text{purchase}} + \eta_{Heat}^{\text{wastecomb}} \cdot C_{Heatpump}^{\text{O\&M}} \\ -(\eta_{Elec}^{\text{wastecomb}} + \eta_{Heat}^{\text{wastecomb}}) \cdot C_{Wastecomb}^{\text{O\&M}})\end{aligned} \tag{4.35}$$

4.1.4. Model optimization

Total costs, total emissions and other services available in the LSC are presented in this section to complete the method of the optimization model.

Emissions

Emissions occur as a result of multiple processes in the LSC. The total emissions are determined according to a balance rule where all component emissions are summed up. Emissions are caused by electricity grid purchase, waste- and sludge transport, incineration, disposal processes and sewage treatment.

$$
\begin{aligned}
em^{\text{tot}}_{LSC,t} = &\sum_{i \in \mathcal{C}} (em^{\text{elgrid}}_{i,Elec,t} + em^{\text{wastetransport}}_{i,Waste,t}) \\
&+ em^{\text{elgrid}}_{LSC,Elec,t} + em^{\text{wastecomb}}_{LSC,Waste,t} + em^{\text{wastedisposal}}_{LSC,Waste,t} \\
&+ em^{\text{sewagetreatment}}_{LSC,Sewage,t} + em^{\text{sludgetransport}}_{LSC,Sludge,t} \\
&+ em^{\text{sludgecomb}}_{LSC,Sludge,t} + em^{\text{sludgedisposal}}_{LSC,Sludge,t}
\end{aligned}
\tag{4.36}
$$

Extensions consider CO_2 prices and the corresponding emission costs.

$$
c^{\text{emissions}} = \sum_{t \in T} \Pi^{\text{CO2}} \cdot em^{\text{total}}_{LSC,t} \tag{4.37}
$$

Total costs

The total costs consist of consumers' costs and LSC operator costs. Consumers' water purchase costs must extend the costs as described in Equation 4.11.

$$
c^{\text{tot,consumers}} = \sum_{t \in T} \sum_{i \in \mathcal{C}} \sum_{j \in \mathcal{S}} c^{\text{total,LSC}}_{i,j,t} + c^{\text{waterdemand}}_{i,Water,t} \tag{4.38}
$$

LSC costs from Equation 4.14 are extended by power costs and costs within the sewage and waste chain.

$$
c^{\text{tot,LSC}} = \sum_{t \in T} \sum_{j \in \mathcal{S}} c^{\text{tot}}_{LSC,j,t} + c^{\text{power}}_{LSC,Elec} + c^{\text{sewagechain}}_{LSC} + c^{\text{wastechain}}_{LSC} \tag{4.39}
$$

Both are summed to form the total model costs.

$$
c^{\text{tot}} = c^{\text{tot,consumers}} + c^{\text{tot,LSC}} \tag{4.40}
$$

Further LSC services

Several services positively affect the LSC. In the GeWoZu, a business model for an electric vehicle pool is set up to increase efficiency in the transport sector. The GeWoZu has multiple modern washing machines with hot water access and implemented heat recovery. An assessment of both services is conducted in the analyses of the demo site.

However, services within the building are not the only factors that can positively impact the LSC. The provision of services from external providers is investigated further. District heat provision by industry and sewage water sale for irrigation are examined in this context. The assessment method for all mentioned services is presented in the Appendix.

4.1.5. Case study

The application of the developed optimization model in the GeWoZu is presented in this section. The study is structured to ensure that all objectives are adequately examined.

First, scenarios without LSC and trading are investigated, considering consumer technologies only. Then, energy trading and LSC business models are gradually introduced. Business model investigations are separated into different scenarios. In the first type of scenarios, the omissions of certain services are analyzed to assess the impact of the services. In the second category of scenarios, market investigations of waste and water business models with different consumer behaviours are examined. The final scenarios analyze the impact and opportunities due to industry services. The workflow of the case study is presented in Figure 4.5. The available services in the case study scenarios are summarized in Table 4.1. LSC Key Performance Indicator (KPI) are defined for the impact assessment of the scenarios. An overview and the definition of the KPIs are presented in Table 4.2.

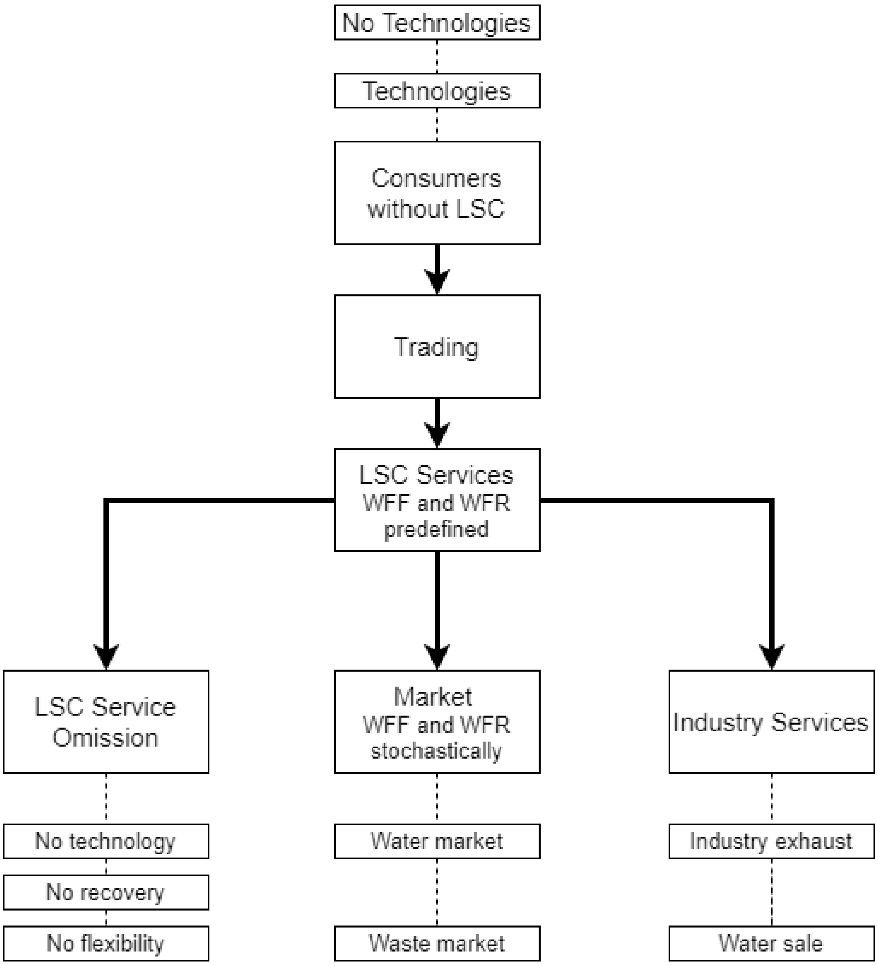

Figure 4.5.: Case study

4.2. Results

The main results of the analyses are presented in this section. Section 4.2.1 shows the results on LSC impacts and Section 4.2.2 presents the effects on the LSC services. Section 4.2.3 and 4.2.4 provide the results for resource markets and external service provisions.

Table 4.1.: Case study scenarios

Scen.	**Consumer tech.**	**Trade**	**LSC business models**	**Energy recovery**	**Flexibility**	**Industry service**
No LSC	✓	x	x	x	x	x
No LSC, no tech.	x	x	x	x	x	x
Trading	✓	✓	x	x	x	x
Base	✓	✓	✓	✓	✓	x
No energy recovery	✓	✓	✓	x	✓	x
No reduction	✓	✓	✓	✓	x	x
No tech.	x	✓	✓	✓	✓	x
No water recovery	✓	✓	x	✓	✓	x
Market scen.	✓	✓	✓	✓	✓	x
Industry service	✓	✓	✓	✓	✓	✓

Table 4.2.: Key performance indicators

KPI	Unit	Definition
Total Costs	€	Total costs for LSC
Emissions	kg_{CO_2}	Total emissions in LSC
Electricity grid consumption	kWh	Total procurement in LSC
Treated waste	kg	Waste treated for energy recovery
Waste reduction	kg	Total reduced and recycled waste
Water reduction	m^3	Total reduced water in LSC
Water pipeline purchase	m^3	Limited water pipeline purchase
Water pool purchase	m^3	Purchase from LSC water pool
LSC water purchase	m^3	Recovered water purchase

4.2.1. Impact of LSC formation

The results of this section present a gradually established LSC, beginning with the introduction of the technology and followed by trading and LSC business models. The introduction of technologies results in a cost reduction from 23 070 € to 20 899 € of 2171 €. Emissions are reduced by about 3 t, or 11.5 % each, resulting in emissions of 23 t. However, only consumers who have their own technologies can gain benefits. The introduction of trading further decreases the LSC costs by 3266€ (14 %) and the emissions by 7.5 t (29 %), where all consumers profit from technology use. LSC purchase and energy recovery leads to a total cost reduction of more than 50 % to 8301 € and

59 % emission reductions to 10.6 t. This result is due to further technology extension, comparably low resource treatment costs and reduced LSC purchase tariffs. Such cost reductions can be achieved only if treatment plant operators charge only real incurred costs. With additional waste disposal costs, costs are reduced to 11 257 €.

Figure 4.6 presents the impact of LSC formation on the electricity sector. Electricity grid consumption decreases as the washing machine and electric vehicle demand coverage is transferred to the LSC operator. Moreover, the demand coverage from the electricity grid drops to 58 % as electricity can also be procured from PV generation and the LSC. Energy recovery has a significant impact on the LSC, as 31 % of the LSC electricity and 34 % of the LSC heat demand can be covered by waste and sludge combustion. Furthermore, more than 30 % of the LSC electricity is sold to LSC members, while only 7 % is procured from LSC members.

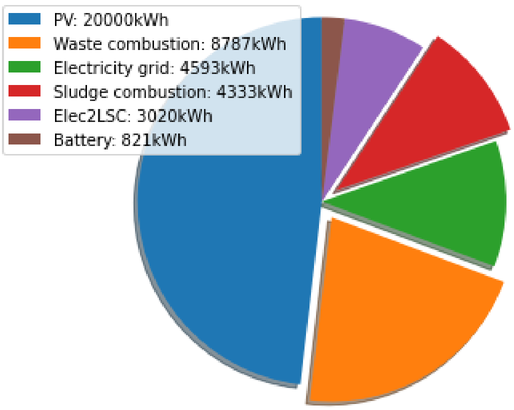

Figure 4.6.: LSC operator electricity input share

The heat map in Figure 4.7 shows that the LSC can cover all of the heating and cooling demand of consumers who do not have their own technologies. However, heat purchase from consumers is not conducted. Instead it is indirectly implemented by electricity purchase and LSC heat pump operation.

Figure 4.7.: LSC heatmap

4.2.2. Service implementation in an LSC

The impacts of different LSC services are compared in this section to find the most effective service in the LSC. Various available services such as resource reduction, water recovery, consumer technologies and energy recovery are removed in different scenarios to assess the service impact. The effect on the KPIs is presented in Tables 4.3 and 4.4.

Table 4.3.: Service omission: energy and environmental KPI

Scenario	**Total costs in €**	**Emissions in** kg	**Electricity grid consumption in** kWh
Base	8301	10549	28031
No tech	10197	12471	37204
No energy recovery	10320	11599	43751
No water recovery	9050	10549	28031
No reduction	9067	11142	26668

Table 4.4.: Service omission: resource KPIs

Scen.	**Treated waste in** kg	**Waste recycling in** kg	**Water reduction in** m^3	**Limited pipeline purchase in** m^3	**Water pool purchase in** m^3	**LSC water-purchase in** m^3
Base	14769	17	351	288	351	414
No tech	14769	17	351	298	351	405
No energy recovery	11764	3010	351	203	351	499
No water recovery	14769	17	351	702	351	0
No reduction	14769	0	0	702	0	665

Consumers cannot sell energy to the LSC without their own technologies. Decreased decentralisation technologies have caused electricity grid purchases to increase by 9173 kWh (32 %) to 37 204 kWh. The emissions increase by 1.9 t or 18 % each, to 12.5 t and the total costs increase by 23 % to 10 197 €. With the omission of energy recovery services, waste and sludge lose their value during treatment. The LSC can thus sell less electricity and heat thereby leading to an electricity grid consumption increase of 15 720 kWh (56 %) to 43 750 kWh and a corresponding emission increase of 1 t (9.4 %) to 11.6 t. The total costs rise by 24 % to 10 320 €. Non-procurement of recovered water causes limited pipeline purchase to rise by 414 m^3 to 702 m^3. Pipeline purchase prices higher than the recovered water prices lead to additional costs of 750 € or a 9 % increase. However, no excess purchase is required due to the implemented LSC water pool. A similar cost increase of 766 € occurs with no reduction and the following omission of the water pool. Total emissions increase by 5.6 % to 11.1 t. However, electricity grid consumption decreases as more sludge is treated, thereby leading to increased sludge treatment energy recovery.

As presented in Figure 4.8, omitting energy recovery leads to the highest cost increase, followed by technology omission. Moreover, technology omission leads to higher CO_2 emissions. No energy recovery has positive effects on the emissions, as less waste and sludge combustion leads to fewer combustion-related emissions. However, the impact is still negative compared with the base scenario. When resources are not reduced, it leads to higher emissions because more resources are treated. As a result, grid consumption is reduced in this scenario. The comparison of the scenarios is presented in Figure 4.9.

As a resource, waste is affected by energy recovery omission only. Recycling and reduction have become more feasible, as garbage has no value in treatment. Water recovery omission produces the same amount of treated sewage without water recovery options. Therefore, water-related costs are affected by non-circular water treatment.

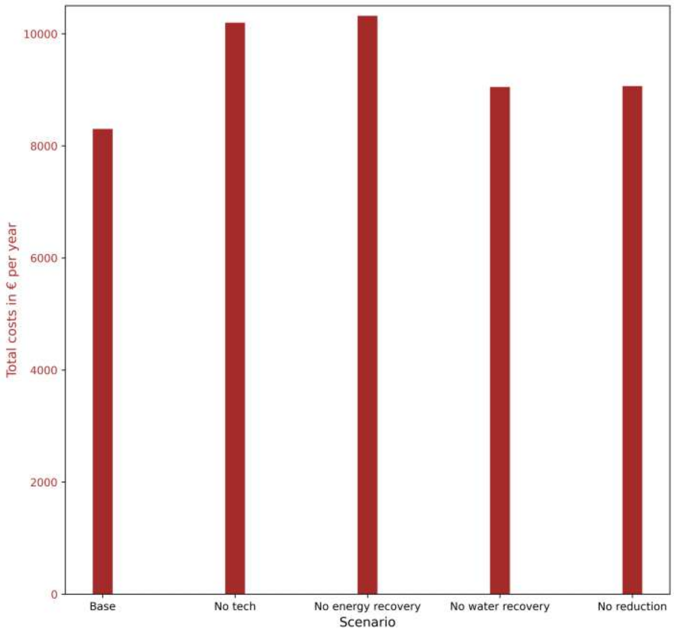

Figure 4.8.: Service omission: costs

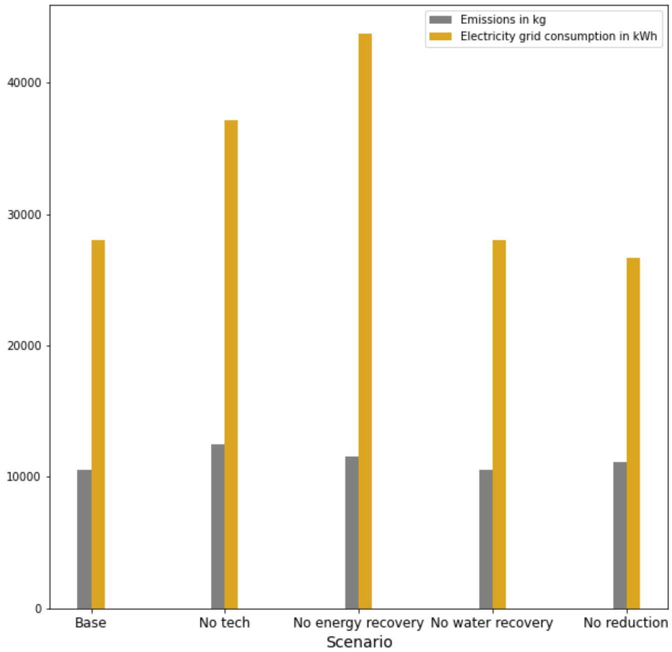

Figure 4.9.: Service omission: emissions and grid consumption

4.2.3. Impact of resource markets

In this section, market investigations are further assessed, beginning with the water market in Section 4.2.3 followed by the waste market in Section 4.2.3. Different WFF and WFR for different consumers are assumed in the analyses.

Water consumption rights trading

Water market impact is investigated by conducting a sensitivity analysis of recovered water from sewage treatment. Figure 4.10 presents the effect of the water market and recovered water on the total costs and pipeline purchase.

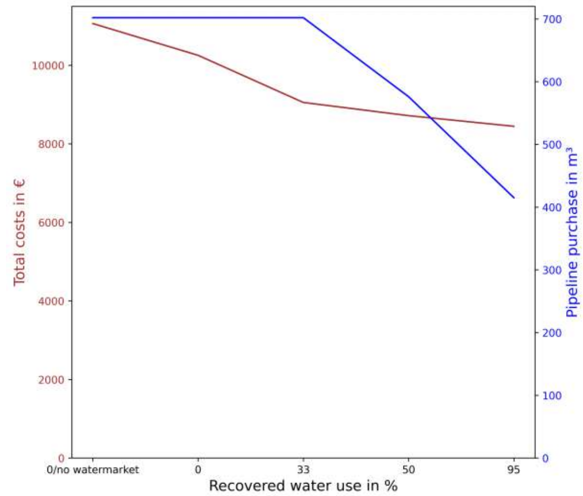

Figure 4.10.: Watermarket overall impact

With less recovered water, limited pipeline purchase experiences an increase. The highest costs arise when no water market and water recovery are implemented. Between 0 % and 33 % water recovery, the cost decrease has the highest gradient, because excess purchase with the highest costs is less needed. The impact on the consumers is presented in Figure 4.11.

The implementation of water recovery positively affects consumers' costs.

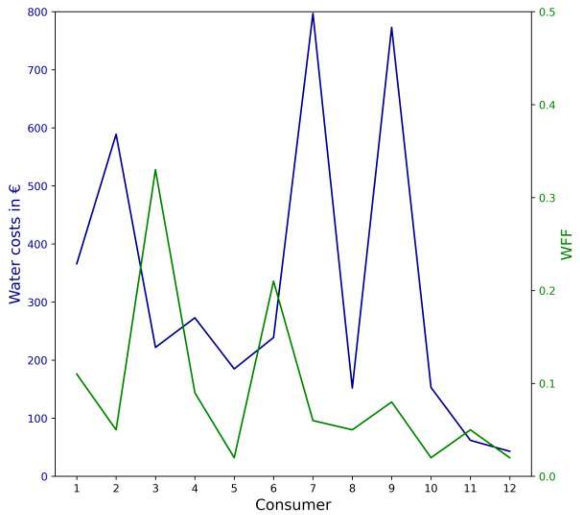

Figure 4.11.: Watermarket consumer impact

However, other factors such as time of use and WFF, also have an impact. Therefore, consumers with lower WFF can also benefit from water pool purchase.

Waste recycling and reduction markets

The waste market price is decreased in a sensitivity analysis, starting from the equilibrium price of Equation 4.35 ($\Pi^{wastemarket}$=0.1457 €/kg). Less recycling is conducted in situations with lower efficient waste market prices, as presented in Figure 4.12. Between 0.0857 €/kg and 0.1057 €/kg, waste recycling increases sharply. At this price, electricity grid consumption and recycling become more economically feasible than waste combustion in more time steps. All waste is recycled at the equilibrium price. With nonlinear decrease of waste recycling and therefore the nonlinear impact on electricity grid consumption, nonlinearities in the costs arise. Rising waste market prices lead to decreasing costs, as presented in Figure 4.13.

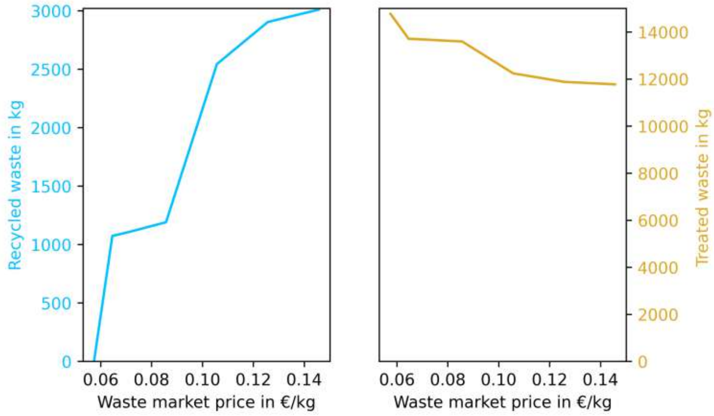

Figure 4.12.: Wastemarket recycling

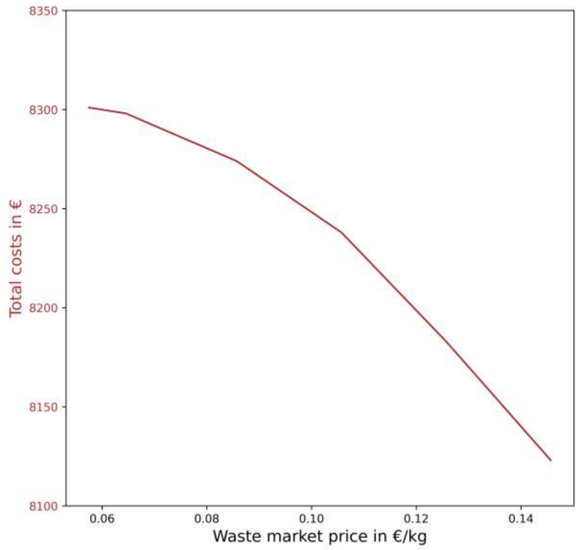

Figure 4.13.: Wastemarket costs

4.2.4. LSC extension: External service provisions

This section presents the impact of exhaust heat and greywater sale services.

Exhaust heat provision

The exhaust heat scenarios differentiate low-price scenarios with prices of 1 ct/kWh and high-price scenarios with 4 ct/kWh. Furthermore, minimum heat procurement contracts are analysed. The impact on total costs, emissions, electricity grid consumption, and the procured exhaust heat are presented in Figure 4.14.

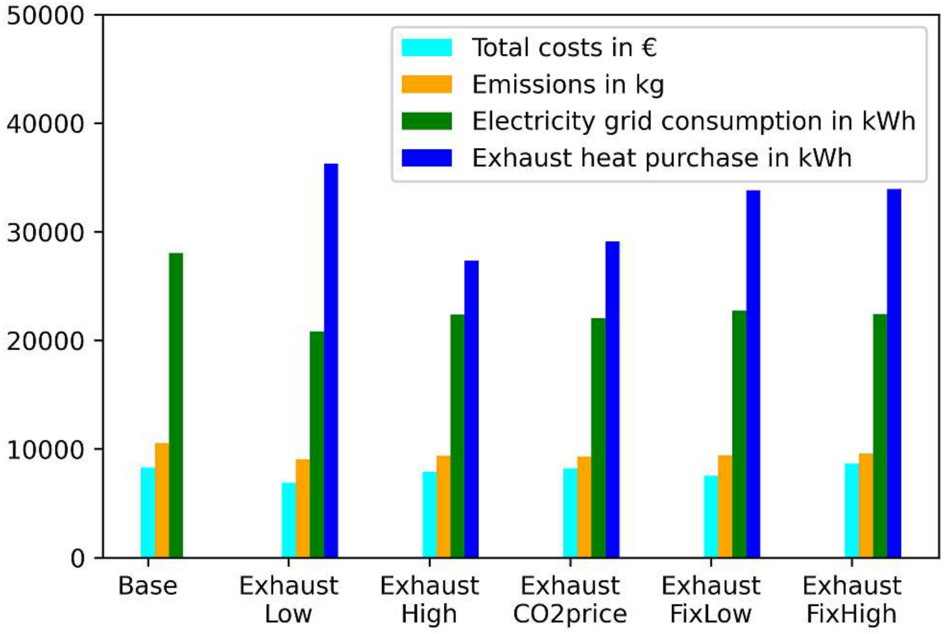

Figure 4.14.: Exhaust heat

The utilization of exhaust heat is strongly dependent on the energy price. CO_2 prices can promote exhaust heat because no emissions are assumed for the procurement. However, fixed consumption agreements lead to decreased efficiency. Emissions and wasted heat rise because heat is not required during the summer. Cost reductions can still be achieved in low-price scenarios, whereas total costs increase in high-price scenarios.

Greywater sale

Different market prices for greywater are assumed in the investigation. The results of the scenario analyses are presented in Table 4.5.

Table 4.5.: Water sale

Sale price in € per m^3	Sold greywater in m^3	Total costs in €
0.375	97.2	7768
0.75	113	7726
1.125	113.5	7684
1.125/no recovery	337	8780

As the water prices increases, water sale increases. The implementation of a greywater market generally leads to a cost decrease. However, the sale is saturated at prices of 75 ct/m^3 because water sale is feasible in certain time steps only. Without water recovery, sewage treatment only has value in sludge energy recovery. All greywater is sold in scenarios without water recovery because of the comparably low efficiency in the sludge chain.

4.3. Discussion

Building upon the results in Section 4.2, the significant findings of the analyses are discussed in this section. Section 4.3.1 discusses the benefits of LSC formation to consumers and to UN SDGs United Nations, 2022. Section 4.3.2 outlines the benefits for different LSC members. Section 4.3.3 provides the impact and suitability of the introduced LSC business models.

4.3.1. Benefits and suitability of an LSC introduction

LSCs are introduced to provide benefits for consumers and for the environment. The results in Section 4.2.1 show that LSCs directly affects consumers' costs and CO_2 emissions. However, the quantity of the benefits depends on the implemented business models, such as available services, in the LSC. The positive contributions of the LSC could be examined across all sectors. Technology demands such as electric vehicles change from being consumers' responsibility to being LSC's responsibility. The same applies to resources, as they are treated cooperatively. The joint demand coverage and resource treatment lead to a broader variety of generation and demand coverage options. Available technologies are used more efficiently within the LSC, such as carpool services for transport demand coverage. Furthermore, introducing modern technologies such as washing machines with hot water access and heat recovery leads to more efficient energy use in the LSC. The introduction of technology further reduces costs and emission. Moreover, washing machine heat recovery can provide significant inputs to the LSC heat sector. Thus minor setup improvements can provide non-negligible benefits to the LSC.

Benefits also arise from the perspective of the SDGs. The establishment of an LSC is directly contributes to SDG goal 11 (Sustainable cities and communities). This contribution is further promoted by LSC financial incentives that lead to cost reductions. Through such incentives, more consumers could be encouraged to participate in LSCs. Furthermore, implemented resource energy recovery can lead to LSC contributions to SDG goal 12 (Responsible consumption and production). As indicated by the results in Section 4.2.1, no resources were disposed of, because an LSC gives resources additional value in energy recovery and recycling. Resource market investigation results in Section 4.2.3 positively impacted responsible consumption, because water reduction was always conducted at its limits. The same applies to waste recycling at sufficiently high prices.

The impact of SDG goal 13 (Climate action) could be examined over all the results in Section 4.2. Additional LSC services and the introduction of resource business models always lead to CO_2 emission reductions. Therefore, the introduction of an LSC with appropriate business models provides a major contribution to SDG goal 13. Moreover, SDG goal 7 (Affordable and clean energy) is promoted by the establishment of an LSC. Consumers can benefit from joint technologies and LSC trading. Even low-income consumers who do note have their own technologies can access clean and affordable energy by participating in an LSC. The resources of all consumers are treated for energy recovery; thus low-income participants also directly impact SDG goal 7. However, clean energy is strongly dependent on the electricity mix. The introduction of an LSC service leads to decreased electricity grid consumption. Given that renewable sources generate a significant share of energy within the LSC, the introduction of an LSC positively contributes to clean energy. Furthermore, scenarios with promoted resource combustion lead to overall emission reductions.

Finally, LSCs contribute to SDG goal 6 (Clean water and sanitation). Sewage and sludge are treated for water and energy recovery; thus water is utilized as a precious resource within LSCs. Therefore, LSCs positively affect the water-energy nexus. Furthermore, the water demand coverage agreement, according to Equation 4.28, leads to water reduction. By giving water additional value in reduction, LSC formation contributes to SDG goal 6. In summary, LSC establishment is an efficient process in contributing to the UN SDGs in decentralized consumer processes.

4.3.2. Benefits for different LSC members

The results in Section 4.2.1 showed that consumers could reduce their total costs by participating in an LSC. Consumers benefit from the services and technologies provided in the LSC and also from generating revenues from waste and water reduction. Thus, the advantage of this situation is that a sustainable mindset is rewarded by LSC business models. Moreover, consumers without such a mindset are encouraged to develop a sustainable perspective. The advantages for consumers participating in an LSC strongly depend on the available services and business models. The results in Section 4.2.2 showed that various services have different impacts on the LSC operation. Consumers can benefit from cost reduction due to the provided services, with energy recovery business models leading to the highest cost reduction. Services can also contribute to sustainable development, because they improve the environmental performance of the LSC.

Industry providers benefit from guaranteed revenues by participating in an LSC, thus offering possibilities for new decentralized plant operators to enter the market, because barriers to entry can be lowered by these guaranteed revenues. Furthermore, service providers can set up innovative business models. The results on exhaust heat provision showed that service providers can generate revenue by participating in an LSC. Business models such as exhaust heat sale offer the possibility of selling energy that would otherwise be lost. This approach allows options to generate alternative values and uses for resources and energy. Moreover, external LSC participants can profit from LSC consumers, as indicated by the results on greywater sale. Aside from receiving financial benefits, service providers can benefit from social and environmental aspects. Participating in LSCs can give companies a positive image, showing that they are a consumer-oriented and sustainable business. However, service providers must still come up with the investment costs, which might become as an implementation barrier.

Overall, benefits for LSC members are mainly due to the community aspect. Advantages are gained by loss of comfort, such as water use reduction. However, actors must be cooperative and ensure that they do not discourage each other. Thus, the fundamental role of the LSC operator in holding the LSC together emerges. Finding an operator that takes all the initiatives can be the primary barrier to establishing an LSC.

4.3.3. LSC business models: Impact and potential implementation barriers

For the business models under consideration, a distinction is made between behaviour encouraging business models and service provider business models. The results in Section 4.2.3 present the behaviour encouraging business models, as consumer actions are rewarded. Incentives to reduce resources are applied by giving resources an alternative value in reduction. The business models for the water market show that water reduction agreements in an

LSC can lead to cost reductions and more sustainable water use due to the introduction of an LSC water pool. However, such business models can backfire, because consumers must be willing to reduce their demand to provide flexibility to the pool. Barriers can also emerge in setting up such agreements with LSC members. The waste reduction business models are only effective with sufficiently high recycling revenues. Without such revenues, waste recycling is not competitive with the alternative value of waste in treatment and energy recovery savings. To promote recycling, policy initiatives should set sufficiently high waste market prices.

The service provision business models as in Sections 4.2.1 and 4.2.2 can have a positive impact. However, bad agreements or contracts with service providers, such as fixed energy procurement agreements, can backfire and lead to a increased costs (as presented in Figure 4.14). Service options such as those in Section 4.2.4 can also be generally beneficial for the LSC, if they allow consumers the freedom of application. Different service provision models can have varying importance to the LSC, as presented in Section 4.2.4. The omission of energy recovery has the highest impact on the total costs. Implemented energy recovery leads to energy and resource efficiency while providing financial incentives for consumers. The omission of consumer technologies leads to the second-highest cost increase. Therefore, an efficient LSC operation requires sufficiently available decentralized technologies. With regard to the CO_2 emissions, the omission of energy recovery is slightly less crucial than the omission of consumer technologies, because of additional emissions from waste combustion. However, emissions are still lower with implemented energy recovery than without due to the emission-intensive electricity grid consumption.

The omission of water recovery affects costs in the water sector only and would not affect the operation of the LSC if no water reduction agreements were made. If such contracts are in place, then water recovery and an LSC water pool (and reduction flexibility) are crucial. Otherwise, reduction agreements could backfire and lead to higher costs. However, when different kinds of LSC business models presented in Section 4.2 are considered, such business models generally have an overall positive impact on LSC participants.

4.4. Resumé

LSCs lead to more efficient energy use and resource utilization. Business models such as trading and service provision can encourage consumers to engage in sustainable behaviour and could further promote resource utilizsation. In general, the establishment of an LSC has a positive impact. However, providing service options and technologies is crucial for cost reductions and energy and resource-efficient operations in the LSC. Several provided LSC services have different impacts on the consumers and the environment. Therefore, before a new service is introduced to the LSC, an impact assessment on consumers and the environment needs to be conducted.

Furthermore, the alternative use of resources has a positive impact on the LSC. However, alternative options such as reduction and treatment tend to be in competition and they depend on the considered scope and defined LSC boundaries. If specific LSC behaviour is to be promoted, then policy actions such as CO_2 prices, reduction targets or energy efficiency measures need to be put in place. Apart from that, LSC feasibility depends on agreements such as those for water reduction and service provider agreements. These agreements do not necessarily lead to an improvement and can even backfire. Thus, the LSC is a complex system that requires a detailed impact assessment before being established.

The developed model provides all necessary applications to investigate the impact of LSC business models. The case study could be performed appropriately in the demo site GeWoZu, as LSC business models lead to energy and resource efficiency. Moreover, the modular implementation provided an efficient modeling framework for analyzing the gradual improvement of LSCs.

4.5. Nomenclature

Sets

$\mathcal{C}$	LSC consumers	index: i
$\mathcal{S}$	Sectors	index: j

$\mathcal{E}$	External sources	index: k
$\mathcal{T}$	Available technologies	index: l
T	Total timesteps	index: t
$\mathcal{D}$	Disposal periods	index: d
$\mathcal{V}$	Available vehicles	index: v

Parameters

C^{in}	Specific input costs	€
C^{out}	Specific output costs	€
Π^{purchase}	Purchase price	€ per [*source*]
Π^{feedin}	Feed-in tariff	€ per kWh
Π^{LSC2cons}	LSC purchase tariff	€ per [*sector*]
Π^{cons2LSC}	LSC sale tariff	€ per [*sector*]
$\Pi^{\text{sector,energy}}$	Energy price LSC	€ per kWh
$\Pi^{\text{sector,grid}}$	Grid charges LSC	€ per kWh
$\Pi^{\text{surcharge}}$	Surcharge LSC price	€ per kWh
$F^{\text{conversion}}$	Conversion factor	$[x^{\text{out}}/x^{\text{in}}]$
X^{Demand}	Predefined demand	[*sector*]
SOC^{start}	Initial state of charge	[*sector*]
$COP^{\text{mean}}_{heatpump}$	Mean coefficient of performance	/
η^{process}	Process efficiency	/
D^{water}	Predefined water demand	m^3
K_{WFF}	Willingness for water flexibility	/
$Prob_{WFF}$	Probability distribution water reduction flexibility	/
$Share^{\text{sewage}}$	Share sewage in water	/
$Share^{\text{greywater}}$	Maximum greywater contribution	/
Ct^{sludge}	Concentration sludge	m^3 per m^3
H_S^{sludge}	Heating value sludge	kWh/m^3
$K^{\text{sewagetreatment,Elec}}$	Electricity demand sewage treatment	kWh/m^3
K_{WFR}	Willingness for reduction and recycling	/
$Prob_{WFR}$	Probability distribution willingness for recycling	/
$\Pi^{\text{wastemarket}}$	Waste market price	€ per kg
Π^{CO2}	CO_2 price	€ per kg CO_2
$K^{\text{energydemand,drive}}$	Energy demand driving	kWh/km
P^{charge}_{max}	Charging power	kW
$Q^{\text{wash,fix}}$	Electricity demand washing fix	kWh

V^{wash}	Heated water volume washing	m^3
$K^{\text{wash,recovery}}$	Heat recovery factor washing	kWh/kgK
ΔT	Temperature difference	K
$\Pi^{\text{industryexhaust}}$	Specific costs exhaust heat	€ per kWh
$P^{\text{industryexhaust}}_{max}$	Maximum exhaust heat power	kW
$F^{\text{watermarket}}$	Water market price factor	/

Variables

c^{tot}	Total costs	€
$c^{\text{O\&M}}$	Operational costs	€
c^{purchase}	Purchase costs	€
c^{disposal}	Disposal costs	€
x^{in}	Sector input flow	$[sector]$
x^{out}	Sector output flow	$[sector]$
x^{purchase}	Purchase flow	$[source]$
x^{feedin}	Feed-in flow	kWh
x^{LSC2cons}	LSC purchase	$[sector]$
x^{cons2LSC}	LSC sale	$[sector]$
soc	State of charge	$[sector]$
$p^{\text{max,elecgrid}}_{LSC}$	Maximum power of grid purchase	kW
c^{power}_{LSC}	Power costs LSC	€
d^{water}	Variable water demand	m^3
$v^{\text{pipe,limited}}$	Limited pipeline purchase	m^3
$v^{\text{water,LSC}}$	Recovered water sewage treatment	m^3
$v^{\text{poolpurchase}}$	Water pool purchase	m^3
$v^{\text{pipe,excess}}$	Pipeline excess purchase	m^3
$v^{\text{water2pool}}$	Water pool feedin	m^3
v^{sewage}	Sewage water	m^3
v^{sludge}	Sludge as by-product	m^3
$q^{\text{sludgecomb}}$	Recovered energy sludge combustion	kWh
$q^{\text{sewagetreat,elec}}$	Electricity demand sewage treatment	kWh
$em^{\text{technology}}$	Technology emissions output	kg CO_2
em^{tot}	Total emissions output	kg CO_2
$bin_{i,v,t}$	Binary variable vehicle for consumer	/
q^{drive}	Energy consumption driving	kWh
q^{charge}	Charging energy flow	kWh

$s_{v,t}$	Driven distance vehicle	km
$q^{\text{wash,tot}}$	Energy demand washing	kWh
q^{washheat}	Energy demand water heating	kWh
$q^{\text{wash,recovery}}$	Recovered heat washing	kWh
$q^{\text{industryexhaust}}$	Exhaust heat industry	kWh
$c^{\text{industryexhaust}}$	Cost exhaust heat purchase	€
$v^{\text{greywater,sold}}$	Greywater to water market	m^3
$v^{\text{greywater,treated}}$	Greywater treated	m^3
$rev^{\text{greywater,sold}}$	Revenues water market	€

Table 4.6.: Model parameters and decision variables LSC

5. Capacity investment, local energy market and circular economy establishment in local sustainable municipalities (LSM)

This chapter presents the extension of the previous analyses on resource utilization in sector coupling to capacity localization and investment decision modeling. It is based on the paper from Maldet et al. (2023b). Thus, it provides research on local energy generation and resource treatment investments in municipalities. The concept of an LSC is extended to a Local Sustainable Municipality (LSM), where investment decisions and energy and resource utilization business models are established at the municipal level.

To fulfil the goals of the RED (European Commission, 2023a), the EU established the directives 2018/2001 [1] and 2019/944 [2] introducing legal frameworks for energy trading in ECs. However, the scope of ECs is wider than community formation on household level. Local municipal governments could establish decentralization in communities and emerge as operators for such communities. Therefore, an LSM establishing a local market on the municipal level is introduced in this chapter.

The local authorities in municipalities operate the LSM, wherein the market

[1](*Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ L 328, 21.12.2018, p. 82–209* n.d.)

[2](*Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199.* N.d.)

for electricity trading between participants is established. Thus, it is a superordinate market compared with local markets between consumers on the household level. LSM business models consider services apart from electricity trading. Resource management, like waste or sewage treatment, is often the area of responsibility of municipalities. However, resources are only treated without further advantage gain. Results in Section 3.2.2 proposed using recovered energy from resource treatment. LSM operations can have a large variety of options for energy recovery, with the foremost opportunity to sell recovered energy to LSM participants at reduced prices. LSM participation can provide benefits for both municipalities and participants in gaining additional revenues for resource treatment and energy procurement at lower prices. Thus, LSM business models consider both energy operations and resource utilization. Therefore, this study analyzes the implementation of such business models into municipalities.

Introducing local resource treatment facilities with implemented energy and resource recovery requires extensive infrastructure planning. Moreover, treatment and energy recovery strongly depend on local conditions such as the number of households, energy demand and potential technology installation at different sites and locations within the municipality. Therefore, a portfolio analysis of the municipality, considering investment decisions in energy generation and conversion technologies, in treatment facilities is performed. The proposed research on LSM business models is applied to the municipality Breitenau am Steinfeld, Lower Austria (Gemeinde Breitenau, 2023).

The core objective of the studies is to define the advantage and scope of the local market on the municipal level, which also considers resource utilization. Therefore, the impacts of different resource treatment options and LSM objectives are addressed. LSM business model investigation in a showcase municipality should encourage other municipalities to implement sustainable energy and resource business models. This chapter presents RUTIS model extensions that address the core objectives. Section 5.1 presents the applied method in the model extension, while Section 5.2 provides an overview of the significant results. Moreover, Section 5.3 discusses the significant outcomes of the results. Section 5.4 gives a resumé of the major conclusions.

5.1. Methods

The elaboration of the investment decision analyses requires the development of an optimization framework on sector coupling in municipalities with portfolio optimization functionalities. Therefore, the RUTIS framework (Maldet, 2022) is extended to investment decisions. This section presents the method applied in the framework extension.

5.1.1. Optimization modeling framework

The model framework analyses consumer participation in local markets in the municipality. LSM participants are aggregated in communities, forming their own local market within the community. While these communities consider operation apart from energy trading, they are referred to as LSC. Figure 5.1 shows the implementation of LSC markets in a superordinate LSM market.

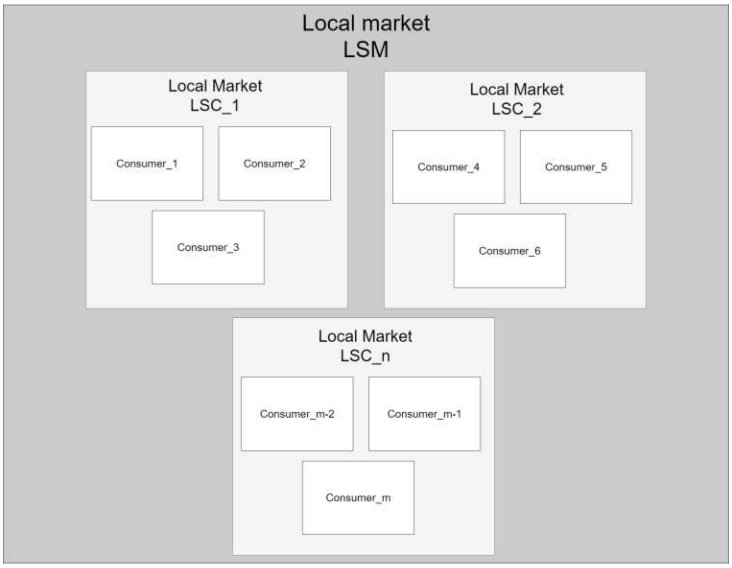

Figure 5.1.: LSM and LSC local markets

Decentralized consumer community operations are performed in LSCs while multiple LSCs can interact in the LSM. Thus LSCs represent consumers in the LSM optimization model. Consumers are aggregated into four different LSCs with similar dimensions. Additionally, the fifth LSC with local municipality facilities is formed and represented in the model. The optimization model considers investment decisions on decentralized consumer technologies to cover the LSC energy and resource demands. Furthermore, the model includes investment decisions on the LSM level, which mainly include facilities for resource treatment. The primary goal of the investment decisions is determining the location of treatment facilities, while the exact capacity assessment has a subordinate role. The combination of multiple-sector investment decisions with community operations and business models results in a high optimization model complexity and long computing times. Therefore, an optimization framework approach decouples investment decisions and operational analyses. Figure 5.2 presents the performed model workflow.

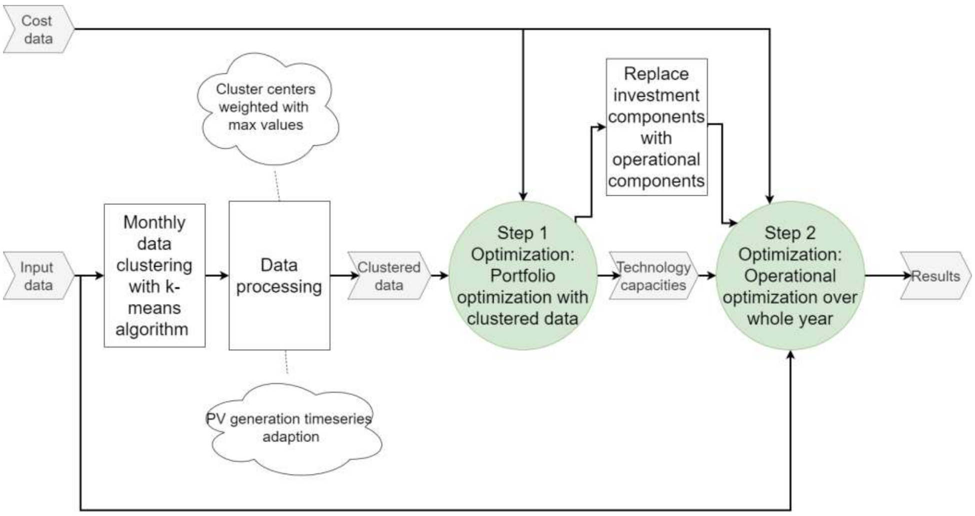

Figure 5.2.: Optimization framework workflow

The portfolio optimization is performed with representative clusters of the data to reduce the model size of the optimization model. Annual input data must be preliminarily processed. Original input data in hourly resolution are transformed into 360 clusters, representing the whole year in a shorter period. Each cluster represents a representative time step of the original data. The clustering is performed with 30 clusters for each month to consider seasonal variance. The applied clustering method is a K-means algorithm, where cluster centers are used as adapted input data for the optimization model. However, more than clustering is needed to gain appropriate input data for the operational model. Cluster centers represent mean values and, required peak capacities for resource treatment are discarded in the clustering approach, resulting in non-feasible operational models due to insufficient treatment capacities. Therefore, the cluster centers are weighted with the maximum value of the input data. This approach provides model workflow improvements in terms of location determination but decreases accuracy in exact capacity determination. To limit the overestimation of PV generation, the clustered generation data are adapted to represent two-week generation input.

The portfolio optimization is applied to clustered input data. Model results of the first step yield the required technology capacities with a major focus on localization. These capacities are provided as inputs to the operational model in step two together with original, hourly resolution input data.

In the second step, the optimization model is adapted so that no investment decisions must be performed. Thus the maximum technology operation capacities are set to the results of model step one. The second step investigates the detailed LSC operation on the LSM market over a year in hourly resolution. Operational optimization over longer periods is required due to seasonal variance and to assess resource planning over a longer period of time.

By performing the two-step optimization approach, capacity locations, capacity estimations and operations in the LSM can be assessed while keeping the model size at an acceptable level. Detailed model methodology in the energy and resource sectors is presented in the following sections.

5.1.2. LSM model equations

LSM introduction and interaction with LSCs include multiple operations such as energy sharing, joint resource treatment and investment decisions. The functionalities presented in Figure 5.3 must be considered in the investigation method.

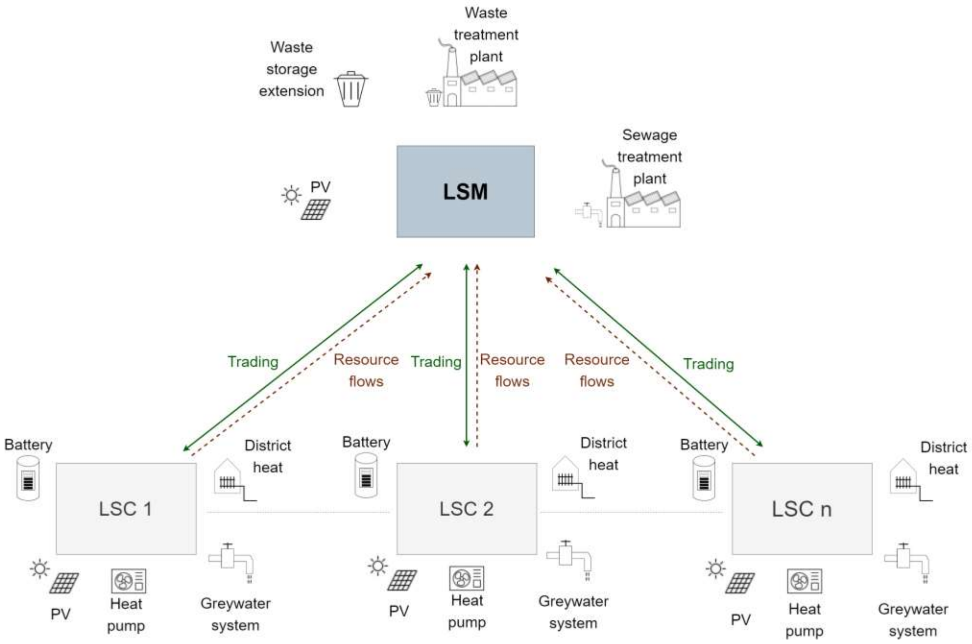

Figure 5.3.: LSM operation

LSM model analyses are performed as cost minimization problems with total costs composed of investment and operational costs, as presented in Equation 5.1. Investment costs are evaluated in the first modeling step, whereas operational costs are determined in the operation analysis.

$$min(z) = min(c^{\text{tot}}) = min(c^{\text{inv}}_{step1} + c^{\text{operational}}_{step2}) \tag{5.1}$$

The model considers technologies investment costs with annuities based on technology amortization rates N_l and weighted average costs of capital $WACC$ (assumed with 3 %). The annuity factor for each technology α_l is calculated with Equation 5.2.

$$\alpha_l = \frac{(1 + WACC)^{\text{N}_l} \cdot WACC}{(1 + WACC)^{\text{N}_l} - 1} \quad \forall l \in \mathcal{T} \tag{5.2}$$

The model considers investment costs in the form of maximum capacity x_l^{max}

based investment costs $C_l^{\text{inv,var}}$ and fixed investment costs for installation or construction for each technology $C_l^{\text{inv,fix}}$. As only a short period of the year is mapped in the first step of the optimization, the costs must be multiplied by a weighting factor F^{year} as the ratio of considered timesteps and total timesteps of a year. The relations are described in Equations 5.3 - 5.5.

$$c_l^{\text{inv,var}} = \alpha_l \cdot C_l^{\text{inv,var}} \cdot F^{\text{year}} \cdot x_l^{\text{max}} \quad \forall l \in \mathcal{T} \tag{5.3}$$

$$c_l^{\text{inv,fix}} = \alpha_l \cdot C_l^{\text{inv,fix}} \cdot F^{\text{year}} \cdot bin_l^{\text{install}} \quad \forall l \in \mathcal{T} \tag{5.4}$$

$$F^{\text{year}} = \frac{T^{\text{cluster}}}{T^{\text{year}}} \tag{5.5}$$

Equation 5.6 presents the total investment costs can be calculated by a summation of investment costs of all technologies.

$$c_{step1}^{\text{inv}} = \sum_{l \in \mathcal{T}} c_l^{\text{inv,var}} + c_l^{\text{inv,fix}} \tag{5.6}$$

Operational costs consist of operational technology costs (Equation 5.7) and costs for external procurement (Equation 5.8) of energy or resource at defined prices Π_k^{procure}, such as electricity grid procurement or water pipeline procurement.

$$c_l^{\text{O\&M}} = \sum_{t \in T} C_{l,t}^{\text{O\&M}} \cdot x_{l,t} \quad \forall l \in \mathcal{T} \tag{5.7}$$

$$c_k^{\text{procure}} = \sum_{t \in T} \Pi_k^{\text{procure}} \cdot x_{k,t} \quad \forall k \in \mathcal{E} \tag{5.8}$$

Moreover, revenues can be generated by the sale of energy or resources, as presented in Equation 5.9.

$$rev_f^{\text{feedin}} = \sum_{t \in T} \Pi_f^{\text{feedin}} \cdot x_{k,t} \quad \forall k \in \mathcal{E} \tag{5.9}$$

The model considers environmental aspects of the LSM in the form of CO_2 emissions. They are calculated by summation of technology and external source procurement emissions by calculation with CO_2 factors F^{CO2} (Equation 5.10) and monetarized by CO_2 prices (Equation 5.11). The emission costs are counted as operational costs. For the construction of capacities, no emissions are assumed, as the optimization focuses on environmental performance in the operation rather than in the whole life cycle.

$$em_t^{\text{CO2}} = \sum_{l \in \mathcal{T}} F_l^{\text{CO2}} \cdot x_{l,t} + \sum_{k \in \mathcal{E}} F_k^{\text{CO2}} \cdot x_{k,t} \tag{5.10}$$

$$c_t^{\text{CO2}} = em_t^{\text{CO2}} \cdot \Pi^{\text{CO2}} \tag{5.11}$$

Equation 5.12 presents the summation of all kinds of operational costs to total operational costs.

$$c_{step2}^{\text{operational}} = \sum_{l \in \mathcal{T}} c_l^{\text{O\&M}} + \sum_{k \in \mathcal{E}} c_k^{\text{procure}} - \sum_{f \in \mathcal{F}} rev_f^{\text{feedin}} + \sum_{t \in T} c_t^{\text{CO2}} \tag{5.12}$$

Detailed information on the considered costs differs between sectors. Furthermore, model constraints are defined to describe the LSM system. Both are presented in the following section.

5.1.3. LSM sectoral costs and constraints

Model constraints consider technology limitations, conversion relations and storage equations as presented in Maldet et al., 2022b. Moreover, equilibrium constraints for each sector must be considered, which is dependent on the available technologies in the respective sector. For balance rules, it must further differ between LSC balance rule and LSM balance rule. Balance rules are graphically represented in the Appendix. Furthermore, energy recovery equations are presented in the Appendix. The goal is always to cover predefined demands. Therefore, sets representing the LSCs and LSM are defined, with the LSM represented at each LSC position.

Waste sector

The LSM is responsible for waste management. Accruing waste from each LSC is allocated to the LSM at a particular geographical position. Moreover, sludge from sewage treatment is counted as waste and must be treated. An investment decision in waste treatment technologies is performed in each LSM position. Waste can be incinerated to recover electricity and heat, whereas 50 % of energy recovery utilization is assumed. Recovered energy is allocated to the corresponding sectors. However, emissions occur due to the share of non-biodegradable waste. Therefore, emissions of 0.125 kg of CO_2 emissions per kg waste are assumed independent of the considered waste treatment option. These emissions are assumed based on IEA Bioenergy (2003) and the share of biowaste and sludge in the municipality. A further option for waste treatment is anaerobic digestion. Generated gas can be incinerated in gas CHP plants or sold on the gas wholesale market. For gas CHP, an investment decision must be performed. Further options are limited external disposal and reduction of waste. Reduction is monetarized by the value of Cialani and Mortazavi (2020). As not all positions must have waste treatment facilities, waste transport between LSM positions is enabled. By binary variables, simultaneous transport input and output is disabled to prevent circular waste flows. This results in the following balance rule for waste in Equation 5.13

$$\begin{aligned} D^{\text{wasteIn}}_{LSC_m,t} + m^{\text{sludge}}_{m,t} + \sum_{n\in\mathcal{M},n\neq m} m^{\text{wastetrans,in}}_{m,n,t} \\ = m^{\text{waste}}_{m,comb,t} + m^{\text{waste}}_{m,AD,t} + m_{m,disp,t} \\ + m_{m,red,t} + \sum_{n\in\mathcal{M},n\neq m} m^{\text{wastetrans,out}}_{m,n,t} \end{aligned} \tag{5.13}$$

Water and sewage sector

Similar to waste, sewage from the LSCs is aligned to the LSM at each position. An investment decision in sewage treatment plants is determined to assess capacity and position of the facility. Like for waste treatment, sewage treatment investment by municipalities is financial participation to larger treatment plants. Electricity is required as an additional input for sewage treatment and must be provided by the LSM. Outputs from sewage treatment include recovered water (assumption 50 % use of recovered water) and sludge (as input to the waste sector). Recovered water can be sold to LSCs at defined prices $\Pi_{i,m}^{waterrecovery}$ depending on the distance between the sewage treatment plant and LSC.

A certain amount of the water demand can be covered by greywater system installation. The share of greywater in sewage is assumed with 50 % whereas kitchen sewage is not considered greywater because of the additional required efforts to extract food remainings (Eawag Das Wasserforschungsinstitut des ETH-Bereichs, 2021), (Allen, 2023). Moreover, it is assumed that only 50 % of the total water demand can be covered by greywater (Christova-Boal et al., 1996). However, the model must perform an investment decision on greywater installation, with potential system installation in each household. This results in a MILP, considering the installed greywater systems as integer variables $int_i^{\text{greywater}}$. The integer variable is limited by the number of households $N_i^{\text{household}}$ in the LSM as presented in Equation 5.14. The total greywater that can be used is calculated by Equation 5.15, considering the unit volume of 12 l/h.

$$int_i^{\text{greywater}} \leq N_i^{\text{household}} \tag{5.14}$$

$$v_{i,greywater,t} \leq int_i^{\text{greywater}} \cdot V^{\text{greywater,unit}} \tag{5.15}$$

The remaining water must be covered by pipeline purchase, resulting into the following water balance rule in Equation 5.16.

$$D_{i,water,t} = v_{i,waterpipe,t} + v_{i,greywater,t} + \sum_{m \in \mathcal{M}} v^{\text{water}}_{i,m,sewage,t} \tag{5.16}$$

Sewage can be transmitted to other positions to prevent multiple treatment plant installations. This leads to the sewage balance rule in Equation 5.17.

$$v_{m,sewage,t} - v_{m,sewagetreat,t} + \sum_{n \in \mathcal{M}, n \neq m} v^{\text{trans,in}}_{m,n,sewage,t} = \sum_{n \in \mathcal{M}, n \neq m} v^{\text{trans,out}}_{m,n,sewage,t} \tag{5.17}$$

Electricity sector

The electricity sector for LSCs considers investment in PV and battery capacities. Excess generation can be fed into the electricity grid. Moreover, electricity can be sold at predefined prices to the LSM, like presented in Equation 5.18.

$$rev^{\text{elec2LSM}}_{i,t} = q^{\text{elec2LSM}}_{i,LSM_i,t} \cdot \Pi^{\text{elec2LSM}}_{i} \quad \forall i \in \mathcal{C} \tag{5.18}$$

LSCs can procure electricity at defined prices and efficiencies from the LSM. Prices and efficiencies are dependent on grid length between the geographical LSC position in the municipality, represented with purchase of LSC at position i from LSM at position m. This is presented in Equation 5.19.

$$c^{\text{LSM2elec}}_{i,m,t} = \frac{q^{\text{LSM2elec}}_{i,m,t}}{\eta^{\text{LSM2elec}}_{i,m}} \cdot \Pi^{\text{LSM2elec}}_{i,m} \quad \forall i \in \mathcal{C}, m \in \mathcal{M} \tag{5.19}$$

Procurement prices are lowered by reduced grid tariffs based on the grid section, resulting into position-dependent electricity grid procurement electricity prices.

The LSCs must provide electricity to heat pumps for heat generation if these are installed. The remaining electricity is procured from the electricity grid, whereas additional emissions for grid procurement are assumed as 0.209 kg/kWh according to Landesamt für Umwelt Brandenburg, 2018. This results in the LSC balance rule in Equation 5.20.

$$\begin{aligned} q_{i,PV,t} + q^{\text{procure}}_{i,elgrid,t} + q^{\text{out}}_{i,bat,t} + \sum_{m \in \mathcal{M}} q^{\text{LSM2elec}}_{i,m,t} \cdot \eta^{\text{LSM2elec}}_{i,m} \\ = D_{i,elec,t} + q^{\text{elec}}_{i,HP,t} + q^{\text{feedin}}_{i,elgrid,t} + q^{\text{elec2LSM}}_{i,LSM_i,t} \end{aligned} \tag{5.20}$$

The LSM can sell electricity to LSCs. This electricity can come from LSC sales to the LSM but also from energy recovery of waste incineration. Moreover, the required electricity for sewage treatment must be provided by the LSM. However, this only accounts if an investment decision is performed in the LSM at a certain position. This results in the balance rule in Equation 5.21.

$$\begin{aligned} q_{m,PV,t} + q^{\text{procure}}_{m,elgrid,t} + q^{\text{elec2LSM}}_{LSC_m,t} + q^{\text{elec}}_{m,comb,t} \\ + q^{\text{elec}}_{m,CHP,t} = \sum_{i \in \mathcal{C}} \frac{q^{\text{LSM2elec}}_{i,m,t}}{\eta^{\text{LSM2elec}}_{i,m}} + q^{\text{elec}}_{m,sewage,t} \end{aligned} \tag{5.21}$$

Heat sector

The internal option for the LSCs to cover the heating demand is the installation of heat pumps. However, as heat can be recovered from waste treatment, the analyses must consider district heating installations. The model applies investment decisions in district heating systems. With district heating capacity installed, LSCs can procure recovered heat at pre-defined LSM prices Π^{LSM2heat} at distance-dependent efficiencies $\eta^{\text{LSM2heat}}_{i,m}$. The procured heat is limited by the installed capacity, as presented in Equation 5.22.

$$q_{i,m,t}^{\text{LSM2heat}} \leq q_{i,DH}^{\text{installed}} \tag{5.22}$$

This leads to the LSC heat balance rule in Equation 5.23.

$$D_{i,t}^{\text{heat}} = \sum_{m \in \mathcal{M}} q_{i,m,t}^{\text{LSM2heat}} \cdot \eta_{i,m,t}^{\text{LSM2heat}} + q_{i,HP,t}^{\text{heat}} \tag{5.23}$$

LSM heat can be generated by energy recovery with waste incineration or biogas CHP. Non-usable heat is considered exhaust heat, resulting in Equation 5.24.

$$q_{m,comb,t}^{\text{heat}} + q_{m,CHP,t}^{\text{heat}} = \sum_{i \in \mathcal{C}} \frac{q_{i,m,t}^{\text{LSM2heat}}}{\eta_{i,m,t}^{\text{LSM2heat}}} + q_{m,exhaustheat,t} \tag{5.24}$$

5.1.4. Case study

The LSM business models' application and optmization framework are tested in the municipality Breitenau am Steinfeld in Lower Austria (Gemeinde Breitenau, 2023). The municipality consists of 1581 residents living in 730 households. Moreover, the case study considers public buildings. Table 5.1 presents the aggregation of residents and public buildings by forming five LSCs. More detailed information on scenario settings is presented in the Appendix.

For the elaboration of the research questions, the study establishes four different scenario settings in the municipality. The "Trading" scenario setting considers sensitivity analyses on PV capacity in the LSCs with a special focus on the impact on LSCs without their own PV installation possibility. Thus the effect of trading over the local LSM market is analyzed. Scenario setting "Circular economy" analyzes waste treatment portfolio optimization by considering waste incineration and anaerobic digestion as significant options. In the "Greywater" scenario setting, investment decisions in separate greywater

Table 5.1.: Municipality configuration

LSC	Residents	Households
1	372	163
2	453	230
3	417	200
4	339	137
5 (public)	-	-

systems and impact on costs and water household are assessed. Finally, scenario setting "Policy and strategy" considers different municipality strategies by monetarizing targets. Table 5.2 summarizes the scenario settings.

Moreover, KPIs are defined to compare community operations in different scenario settings. These KPIs are summarized in Table 5.3. The non-local LSM utilization parameter is defined in Equation 5.25, considering the ratio of fed-in electricity $q_{elgrid}^{\text{feedin}}$, exhaust heat $q_{exhaustheat}$, disposed waste m_{disp} multiplied with its heating value H_S^{waste} and externally sold gas $q_{gassale}$ to sum of total electricity $d_{el,total}$ and heat demand D_{heat}, accruing waste $M_{waste}^{\text{accruing}}$ and total generated gas $q_{wasteAD}^{\text{gas}}$. The total electricity demand is set together of pre-defined electricity demand D_{el}, electricity demand for heat pumps q_{HP}^{elec} and electricity demand for sewage treatment q_{sewage}^{elec} according to Equation 5.26.

$$\sigma^{nonLocal} = \frac{q_{elgrid}^{\text{feedin}} + q_{exhaustheat} + H_S^{\text{waste}} \cdot m_{disp} + q_{gassale}}{d_{el,total} + D_{heat} + H_S^{\text{waste}} \cdot D_{waste}^{\text{accruing}} + q_{wasteAD}^{\text{gas}}} \tag{5.25}$$

$$d_{el,total} = D_{el} + q_{HP}^{\text{elec}} + q_{sewage}^{\text{elec}} \tag{5.26}$$

Table 5.2.: Scenario settings

Scenario setting	**Description**
SC1: Trading	Impact assessment of trading on local markets
SC2: Circular economy	Waste treatment portfolio optimization
SC3: Greywater	Profitability analysis on separate greywater systems
SC4: Policy and strategy	Analysis on different policies and strategies by monetarizing objectives
Self-sufficiency policy	Strategy by modeling high electricity grid procurement costs
Low-emission policy	Modeling of high CO_2 prices to lower emissions
Local-efficiency policy	Keeping energy and resources in the municipality loop by penalizing electricity grid feedin and exhaust heat
2040 scenario	Scenario setting to give policy recommendations: CO_2 neutral electricity mix and CO_2 prices of 350 €/t

Table 5.3.: Key performance indicators

KPI	Unit	Description
Investment costs	€	Total costs for technology investment
Operational costs	€	Total costs in the LSM operation
Total costs	€	Total costs (= sum of investment costs and operational costs)
Total CO_2 emissions	t	Total emissions from all LSC and LSM processes
Electricity grid purchase	kWh	Total procurement from electricity grid
Electricity grid feeding	kWh	Total electricity fed into the grid
Exhaust heat	kWh	Non-usable heat from energy recovery
Non-local LSM utilization of energy and resources	-	Non-LSM use parameter according to Euqation 5.25
Electricity to LSM	kWh	Total electricity sold from LSCs to LSM market
LSM to electricity	kWh	Total electricity procured by LSCs from LSM market

5.2. Results

This section summarizes the results of the scenario settings presented in Table 5.2. Each scenario setting is represented by a chapter in this section, beginning with the trading analyses in Section 5.2.1, followed by the circular economy results in Section 5.2.2 and results on greywater utilization in Section 5.2.3. Section 5.2.4 concludes the result section.

5.2.1. LSM technology and market implementation

The results in this section present the impact of PV installation in the LSM with and without the establishment of electricity trading on LSM market. Resource utilization is implemented in the form of joint treatment, but recovered energy procurement is exempted. Moreover, the results of a sensitivity analysis in the same setup with no PV installation by LSC1 and LSC4 are presented.

PV investment is executed to the maximum possible capacities at all LSM positions, independent of trading implementation. Introduction of trading has only a minor impact on the total costs, leading to a cost reduction of 0.25 % from 1.568 M€ to 1.564 M€. Emissions decrease by 0.76 % to 650 t. Electricity grid consumption decreases by 1.2 % to 7833 MWh. Electricity sale from consumers to the LSM market is conducted at 21.3 MWh per year, while electricity procurement is only performed at 6.3 MWh per year. The LSM uses the difference for the operation of the sewage treatment plant. The impact changes in the sensitivity analysis with less PV. Without trading, the total costs would increase by 8.4 % respectively 139 k€. Electricity grid consumption rises by 651 MWh (24 %) and the total emissions increase by 136 t (17.3 %). Introduction of trading over the LSM market leads to a cost decrease of 96 k€ (5.6 %), an emission reduction of 130 t (16.5 %) and a grid consumption decrease of 62 MWh (22.5 %). Figure 5.4 presents the total costs for different PV and trading settings, showing a shift from operational costs to investment costs with PV installation and a cost increase without LSM market trading.

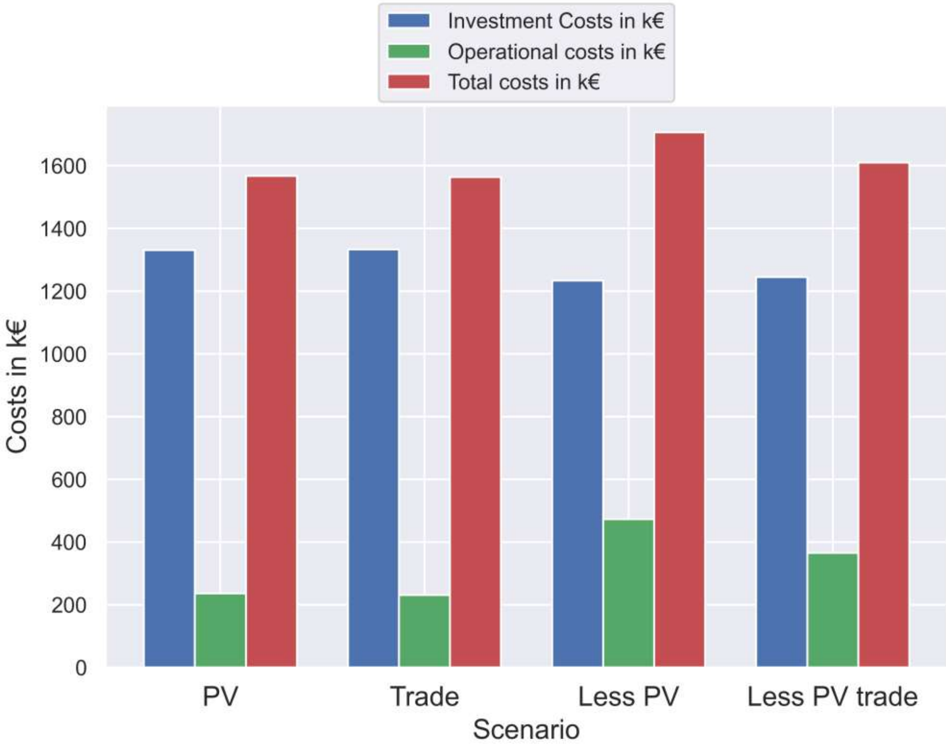

Figure 5.4.: Comparison of total costs for the LSM setup (PV), trading implementation (Trade) and the sensitivity analysis without trading (Less PV) and with trading (Less PV trade)

Compared with the setting with maximum possible PV installation, the sale of electricity via the LSM market increases by a factor 34 to 725 MWh while LSM electricity procurement increases by a factor 112 to 701 MWh.

Figure 5.5 presents the sensitivity analysis trading allocation, where LSCs without their own PV installation benefit from additional local market procurement due to increased purchases from other LSCs. However, the figure shows that LSCs without PV is not the highest profiteer from trading.

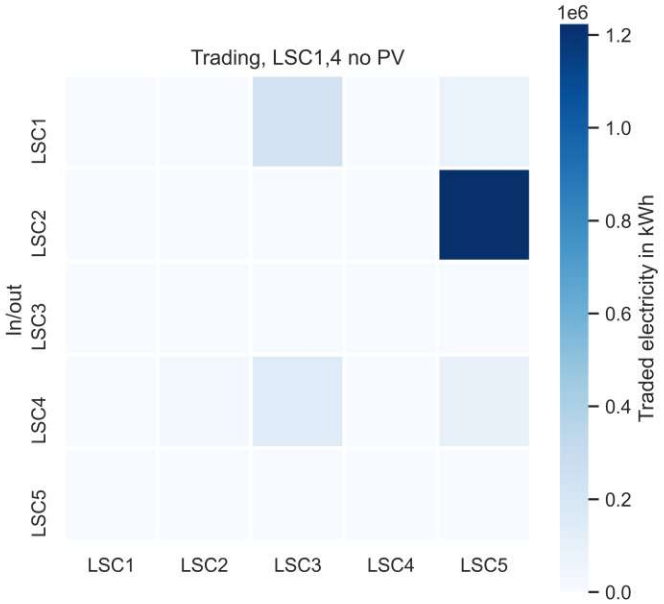

Figure 5.5.: LSM trading flow allocation for sensitivity analysis

5.2.2. Circular economy in LSM

The setup in the previous section is extended to waste and sewage treatment energy and water recovery implementation. The analyses focus on treatment plant localization and treatment portfolio determination. For the comparison between different portfolios, the analyses consider a sensitivity analysis on energy recovery from waste incineration. Moreover, the alternative treatment option of waste anaerobic digestion is investigated as additional setting adaption.

Energy recovery in the LSM has an impact on treatment facility localization. Without energy recovery, the installation of treatment plants is conducted at LSC3, as it is the position with the shortest transportation distance to other locations. Sewage treatment plant localization has no impact on the model outcome, whereas with enabled trading, sewage and waste treatment plants are installed simultaneously. Moreover, trading changes the treatment plant position from LSC3 to LSC4, as LSC4 has the lowest PV installation

Table 5.4.: Waste incineration energy recovery sensitivity analysis

Setting	Trade, no recovery	20% recovery	50% recovery	90 % recovery
Battery in kWh	146	119	60	39
District heat in kW	0	47	114	205
LSM electricity sale in MWh	21.2	1.3	0.4	0
Total emissions in t	650	600	532	447
Total costs in M€	1.56	1.47	1.42	1.37

potential compared to the electricity demand.

Different waste incineration energy recovery utilization yields technology installation differences. Table 5.4 presents the results of the performed sensitivity analysis.

Battery installation decreases, replacing time-flexibility of battery storages by waste storages. District heat installation increases to use a higher share of recovered energy. Moreover, electricity sale by LSCs via the LSM market is minimized. Emissions and total costs decrease with increasingly recovered electricity and heat, leading to cost efficiency with recovered energy from waste treatment.

Replacement of waste incineration by anaerobic digestion ("WasteAD"), and joint consideration of both treatment options ("Portfolio") have a direct impact on total costs and emissions. Figures 5.6 and 5.7 show the comparison between the technology installations, emissions and costs of different waste treatment options; costs and emissions directly correlate in the setups.

Waste anaerobic digestion leads to a cost increase of 32 % and an emission

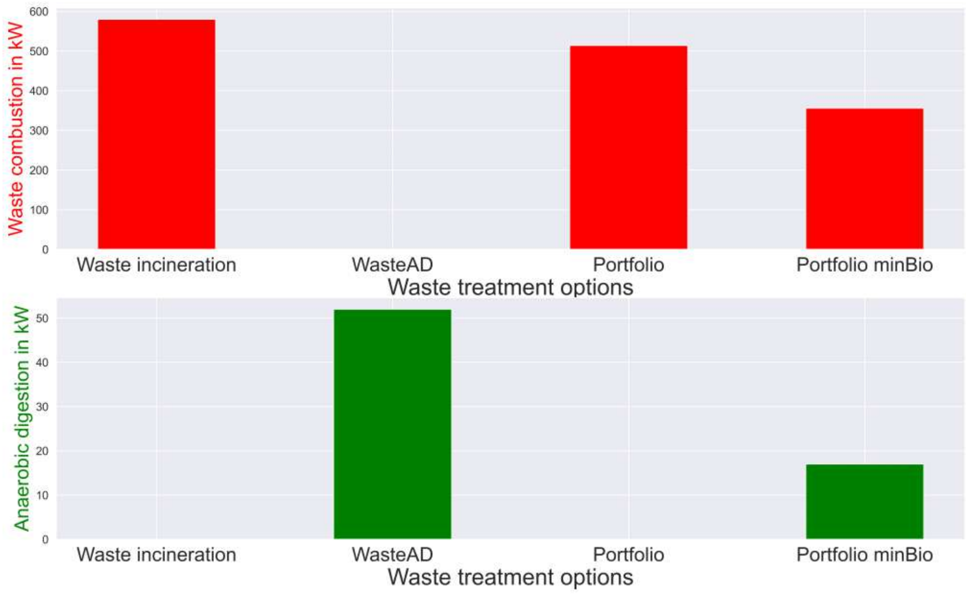

Figure 5.6.: Circular economy waste treatment installation at different available waste treatment options and goals

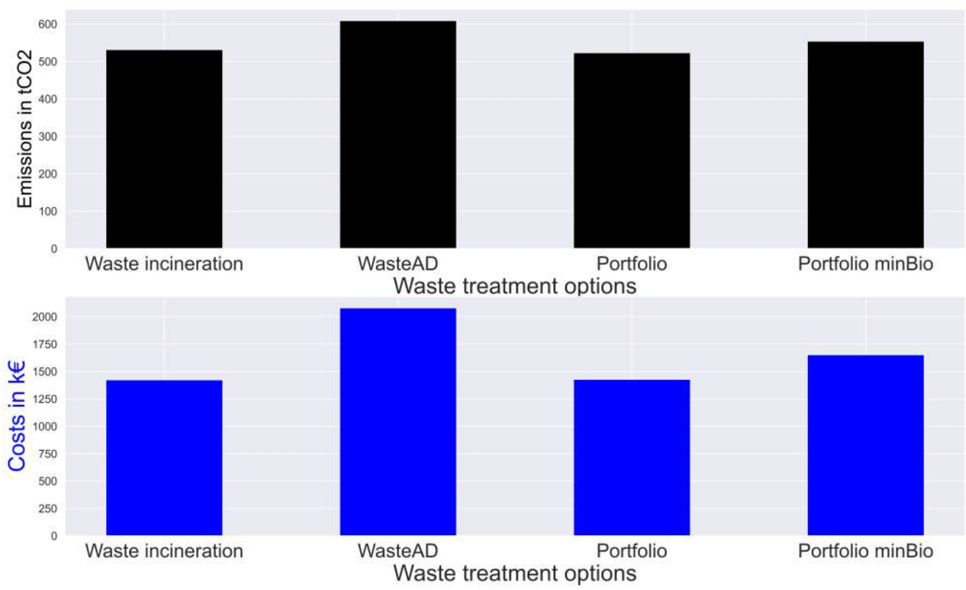

Figure 5.7.: Circular economy costs and emissions at different available waste treatment options and goals

increase of 12.6 %. Portfolio analyses with competing technologies lead to waste incineration plant installations only. High gas prices on its wholesale market do not lead to additional investment in anaerobic digestion plants. By setting biowaste treatment targets for biogas production (“Portfolio min-Bio”), 27 % of the waste treatment facility capacities are anaerobic digestion plants. 61 % are waste incineration capacities, while the remaining 12 % of waste are reduced which leads to an efficient means of a circular economy. However, such goals increase the costs by 13.6 % and the emissions by 5.6 % due to increased electricity grid consumption. Exhaust heat and electricity grid feedin are reduced with increased use of anaerobic digestion.

5.2.3. Greywater utilization

This section presents the analyses on separate greywater systems. The waste portfolio optimization setup from Section 5.2.2 is extended to greywater installation options. Analyses with and without minimum greywater utilization goals are performed. Such goals are necessary for greywater systems to be installed due to the high investment costs of separate systems and the efficient usage of water recovered from sewage treatment. However, without sewage treatment water recovery, greywater installation is done at 99 households in the LSM. The same results emerge for minimum greywater utilization goals. Water procurement from alternative options to pipeline purchase increases from 27 % to 33 %. Required sewage treatment capacity decreases by 2 m^3 to 7 m^3 compared with scenarios without greywater utilization. Moreover, waste incineration capacity decreases by 105 kW to 475 kW due to less sludge emergence. This leads to a decrease of district heat installation by 7 kW (6.9 %) due to less recovered heat. Table 5.5 compares the results from SC3 (greywater utilization) to settings from SC1 (trading without energy recovery) and SC2 (waste portfolio optimization).

Electricity grid consumption increases by 2 % and total costs increase by 2.3 % compared with the same setting without greywater goals. However, fed-in electricity (0.3 %), exhaust heat (7.8 %) and total emissions (1.7 %) decrease. Compared to settings without energy or water recovery, greywater utilization leads to an improvement in all presented KPIs.

Table 5.5.: Setup comparison between casual LSM operation without energy recovery, waste portfolio analysis with energy recovery and greywater utilization

Setting	Trade, no recovery	Waste portfolio	Greywater utilization
Elec. grid purchase in MWh	2114	1609	1642
Elec. grid feedin in MWh	7806	8167	8142
Exhaust heat in MWh	0	500	461
Total emissions in t	650	523	514
Total costs in M€	1.56	1.43	1.46

5.2.4. LSM policy and strategy

In the final result section, different LSM policies and strategies are compared. The setup considers all waste portfolio options. Results in this section present the impact of different policies and strategies on the KPIs and investments and investigates other impacts in terms of total costs, emissions, self-sufficiency and local energy and resource utilization.

Policy impact

This section presents the impact of different LSM policies presented in Table 5.2. Self-sufficiency and low-emission policies lead to similar results, as the electricity grid is the strongest source of emissions in the LSM. Thus, for policy comparisons, low-emission scenarios are considered. The 2040 policy investigations consider analyses on the same settings as in basic policies, with only difference of zero-emission electricity mixes and high CO_2 prices. Furthermore, a scenario with a zero-emission waste anaerobic digestion and recycling combination is considered in a different strategy. The impacts on investments are presented in Figures 5.8 and 5.9. The installed waste treatment plant strongly depends on LSM policies and strategies. Without specific targets, waste incineration is the installed waste treatment technology.

Low-emission strategies lead to increased incineration plant installations at various LSC positions to avoid transport of waste. However, this leads to increased overall waste incineration capacities of 73 %. Local utilization also leads to additional waste incineration capacities of 47 % to treat waste when the recovered energy is needed in the LSM. Anaerobic digestion is only utilized in 2040 scenarios if it is possible to make the process emission-free through additional recycling.

PV installation decreases from 5053 kWp by 70 % to 2161 kWp in the local utilization scenario to avoid electricity feedin as much as possible. Moreover, the LSM installs additional PV capacity in the low-emission scenario to prevent electricity grid consumption. Other scenarios consider the maximum possible PV installation at LSCs of 7214 kWp without separate LSM PV generation. Battery investments increase by 88 % in low emission policies and by 32 % in local-utilization policies. These two strategies thus lead to the highest increases in battery investments. Strategies with zero-emission anaerobic digestion lead to additional battery investment due to lower waste treatment process efficiency. Heat pumps are the main source of heat in all scenarios. However, installed district heat capacities vary depending on the employed strategy. Additional waste incineration plant installation leads to higher energy recovery and thus to increased district heat installation.

Figure 5.10 presents the impact of employed strategies on total costs and emissions. Low emission policies lead to an emission decrease of 26 % and to additional costs of 24 % owing to more required investment. Local utilization strategies lead to sharply rising costs by 49 % but only slightly declining CO_2 emissions by 6 %. The 2040 scenarios lead to cost decreases (6.7 %) due to assumed lower electricity prices and emission decreases (64 %) due to zero-emission electricity mixes. Low-emission strategies in 2040 are not impacted due to low emissions in centralized generation technologies. However, a reduction in emissions of 96 % compared to standard policies can be achieved by establishing zero-emission anaerobic digestion technologies. The disad-

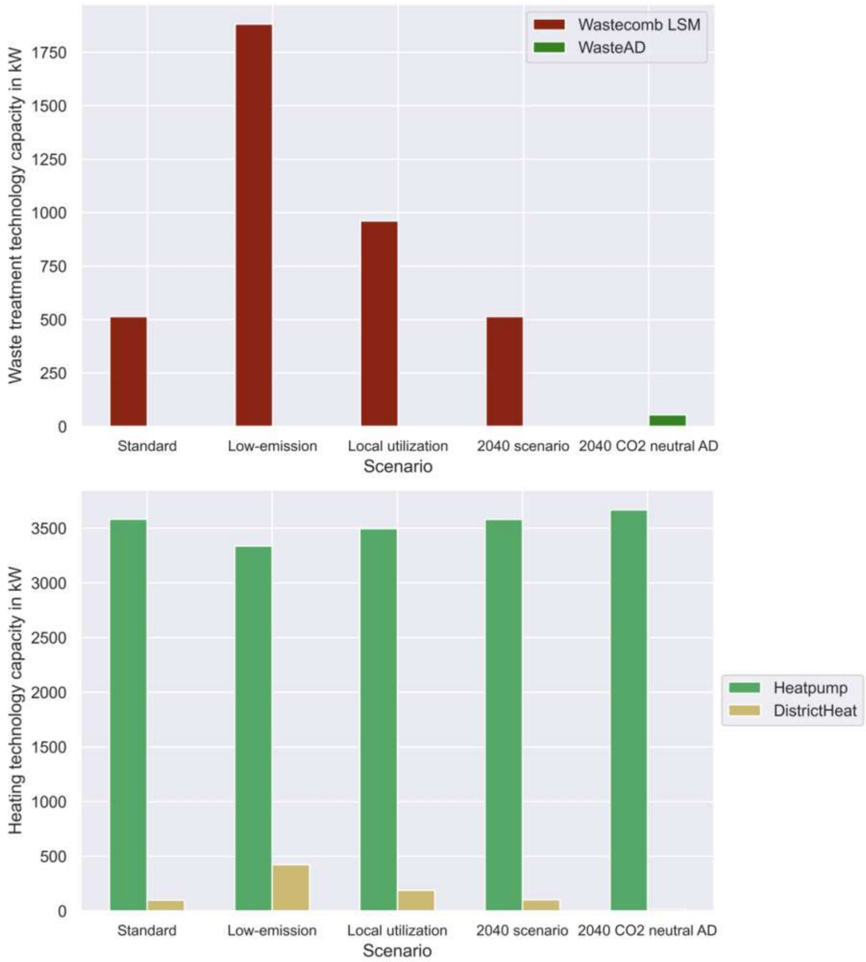

Figure 5.8.: Strategy and policy impact on waste and investments

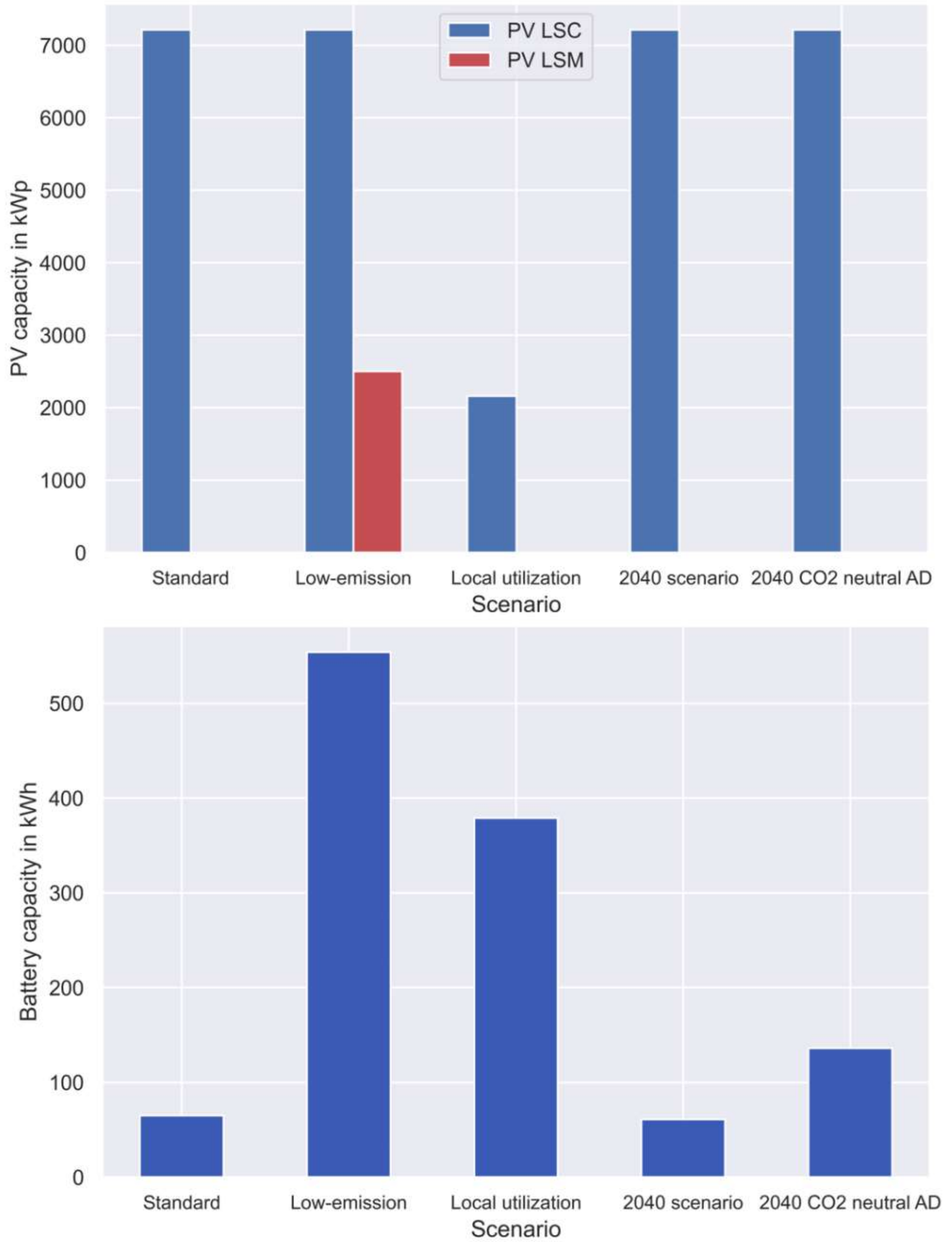

Figure 5.9.: Strategy and policy impact on electricity investments

vantage is an accompanying cost increase of 33 % compared to traditional policies.

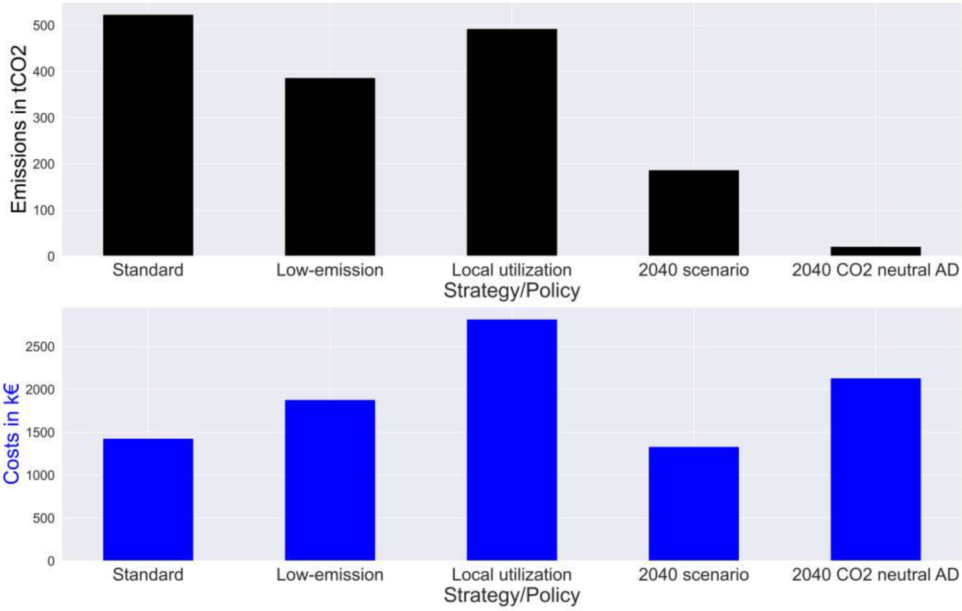

Figure 5.10.: Strategy and policy impact on costs and emissions

Policy comparison

Finally, results in this section present a comparison of the proposed LSM policies and strategies. Figure 5.11 shows the comparison based on total costs, total emissions, electricity grid consumption and non-local utilization based on percentage of impact compared to maximum impact. Grid consumption represents the self-sufficiency of the LSM.

Only price drops can achieve cost reduction in centralized generation, with the 2040 scenario being the only setup leading to lower costs. All policies can achieve emission reduction, although the costs required for reduction differ. Grid consumption is the lowest for low-emission scenarios, as the electricity grid is the main source of emissions (except from 2040 scenarios). The results show a similar local resource utilization for all strategies except

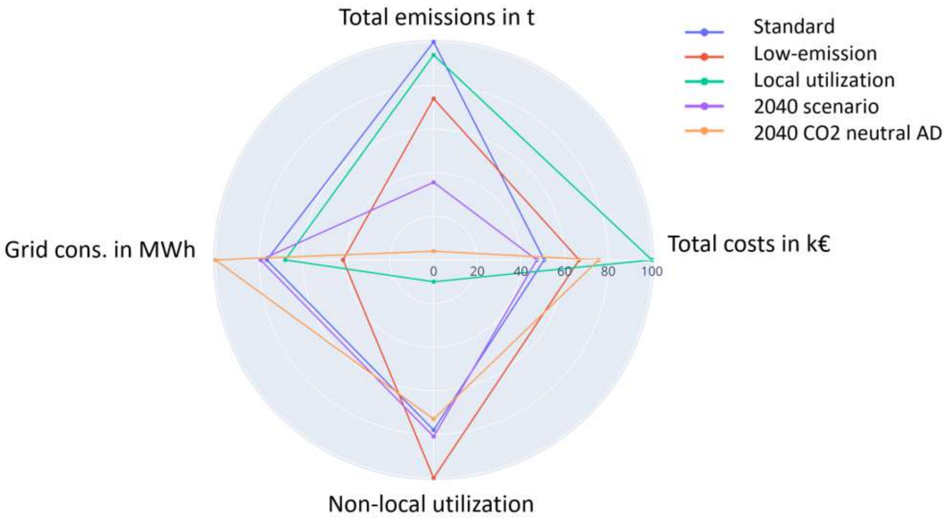

Figure 5.11.: Policy impact comparison on self-sufficiency and local utilization as percentage of maximum achievement

for those designed to reach this goal. Particular strategies lead to the highest local utilization, with a parameter improvement of 50 %. However, costs and emissions increase disproportionately to achieve the goal.

5.3. Discussion

This section discusses the synthesis of the significant results in Section 5.2, beginning with a discussion on market scopes of the introduced LSM market in Section 5.3.1. Building upon that, Section 5.3.2 discusses the impact of implemented energy and circular economy business models regarding the UN SDG (United Nations, 2022). Finally, section 5.3.3 provides a discussion of different LSM goals and strategies.

5.3.1. Local market scopes

LSM markets emerge as superordinate markets to local markets in communities, such as LSCs. Results in Section 5.2.1 show a significant operation on the LSM market. The provided platform for local trading can emerge as a cost-reduction opportunity for participants by providing options to sell their excess energy and procure energy from LSM technologies or other participants. Furthermore, with LSM introduction, the municipal government could emerge as a driver for community establishment. Results in Section 5.2.1 did not consider the utilization of resource treatment energy recovery, leading to a high share of electricity sale of participants via the LSM market. Thus, the LSM marketplace has similar functionality as a local market in communities, with the difference being that the LSM has a high electricity demand for processes such as sewage treatment. Excess electricity can thus be used in a community where the majority of participants have a surplus of PV electricity simultaneously.

Moreover, Figure 5.5 shows that the LSM market could be an opportunity for consumers without PV installation options, as they can benefit from the procurement of cheaper energy. Community building of people of the same income classes and thus social exclusion can be prevented by a public marketplace. Even though directives of the EU on ECs demand non-discriminatory access of consumers to local ECs, consumers might be deterred from insisting on such laws [3].

The impact of electricity sale on the LSM market changes when energy recovery utilization is implemented. Table 5.4 shows a decline in electricity sold by LSM participants with an increasing share of used energy recovery from resource treatment. Therefore, if a municipality can utilize high-capacity energy generation technologies, the local market changes from providing an option for electricity sale to provide cheap energy for participants. This leads

[3](*Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ L 328, 21.12.2018, p. 82–209* n.d.; *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199.* N.d.)

to an inversion of the energy flows in the LSM. In such cases, the LSM is more of a centralized energy provision approach implemented in decentralized local markets. Thus, the LSM market has a different scope than local markets on the community level leading to a distinct division of competencies. Local markets in communities provide more of a socially encouraged energy sharing for lower energy amounts, whereas LSM markets encourage decentralization and energy recovery of resource treatment facilities. However, both markets implemented simultaneously can provide a large variety of options for consumers to take part in local energy markets.

5.3.2. Sustainable LSM energy and resource utilization

LSM utilization became an opportunity for consumer engagement in sustainable operations. Sharing of renewable energy in the LSM can contribute to sustainable operations, as presented by the results in Section 5.2.1. Results in Section 5.2.2 show further opportunities for energy recovery utilization. However, the impact is dependent on the utilized share of energy recovery (Table 5.4) and the provided waste treatment options (Figures 5.6 and 5.7). In a fully considered waste treatment portfolio, waste incineration is the technology to be considered due to its higher efficiency compared to waste anaerobic digestion. The environmental performance of both technologies is the same, as the non-biodegradable share of waste leads to emissions in both technologies due to alternative disposal in anaerobic digestion. Without energy recovery, the installation of treatment plants is undertaken at the site with the shortest distance to other consumers. Trading implementation changes the site to the location with the highest excess energy. Energy availability has a higher impact than transport distances. However, it is unrealistic for each municipality to invest in its treatment facility. Therefore, the investment should be seen as municipalities' financial participation in a multi-municipality treatment plant. Moreover, the required grid infrastructure for recovered electricity and heat distribution must be installed. Thus, despite high waste treatment decentralization potential, implementation barriers in supplementary infrastructure availability and high investment costs might emerge.

Greywater utilization is not performed from a financial perspective. However, as water efficiency is increased, greywater can emerge as an opportunity to prevent water scarcity. Therefore, greywater installation could gain significance from an environmental perspective. Furthermore, technology installation is dependent on resource utilization. Table 5.4 shows decreasing battery installation with rising energy recovery share. Waste storages replace battery storages for time-flexibility in the energy system. Moreover, district heat installation is crucial to use recovered heat from waste incineration.

From the perspective of the UN SDG (United Nations, 2022), LSM introduction is a direct contribution to SDG 11, sustainable cities and communities. Moreover, contributions to SDG 7, affordable and clean energy, emerge by providing clean energy over a local market. SDG 6, clean water and sanitation, and SDG 12, responsible consumption and production, are addressed by the implementation of the circular economy business model implementation. All LSM actions can contribute to SDG 13, climate action, on the municipal level.

5.3.3. Impact of LSM goals and policies

Results in Section 5.2.4 provide insight into LSM policy impacts. Figure 5.8 shows inefficient waste incineration facility installation to reach specific municipality goals by better-timed operation. Moreover, Figure 5.10 indicates that LSM strategy employment always leads to cost increases. However, emissions can be reduced by appropriate strategies. Figure 5.11 shows that low-emission policies lead to high self-sufficiency in current setups owing to emission-intensive electricity mixes. However, to reach emission reduction, the accruing cost increase must be covered. The difference must either be covered by municipalities or by governmental actions in the form of higher CO_2 prices. Furthermore, Figure 5.11 shows that local utilization strategies are inefficient, leading to high cost and emission increases. Therefore, such strategies should not be pursued with it.

Future policies lead to emission decreases due to zero-emission electricity grid procurement, as presented in Figure 5.10. However, the 2040 emission reduction policies only have a minor impact on the municipal level. Process efficiency improvement, such as waste anaerobic digestion with alternative treatment of non-biodegradable waste can provide opportunities for further emission decrease. However, technology improvement leads to rising costs, which municipalities must cover. In summary, municipalities must have clear objectives. Moreover, municipalities must expect increasing costs to be covered when implementing strategies to achieve specific objectives.

Employed strategies can further be affected by the European legal framework in the RED (European Commission, 2023a). According to the directive, energy from waste incineration should only count as renewable by preliminary removing of fossil share of materials (umweltwirtschaft.com, 2022), as waste is never incinerated without such share (Vähl, 2022). However, waste treatment plant operators have concerns over energy security (Eijk, 2022). The LSM analyses indicate significant contributions of waste incineration to total emissions. These emissions are low compared to emissions from electricity grid procurement, leading to higher total emissions in the short term by prohibiting waste incineration. Moreover, in contrast to natural gas, waste is a safely available resource for energy generation. However, future decarbonized energy systems should consider alternative zero-emission waste treatment options, immediate omission of waste incineration plants could backfire in terms of emission reduction and energy security. Therefore, until a phase-out of fossil fuels in the electricity mix can be achieved, waste incineration could emerge as a bridge technology.

5.4. Resumé

LSMs could provide a marketplace for the sale of municipality residents' excess energy and for the procurement of recovered energy from waste treatment. However, the local LSM market is similar to a centralized approach, implemented in decentralized energy systems due to significant energy generation capacities from waste treatment. Therefore, the focus of trading should be set on LSC operations with smaller scopes of communities.

The LSM market should be set up as a higher-level local market with the provision of decentralized energy and resource treatment to LSM members at predefined prices.

Planning of waste and sewage treatment facilities should be performed based on energy availability rather than transport distances. Resource treatment can be efficiently implemented in LSM business models, with waste incineration being the most efficient treatment option. It can provide a dispatchable energy generation option of safely available resources and should thus not be prohibited until the energy transition is further advanced. Anaerobic digestion can emerge as a treatment option in low-emission scenarios when emissions from non-biodegradable waste can be avoided in the process. However, the utilization of energy recovery requires efficient decentralization of treatment facilities and the availability of grid infrastructure. Greywater system installation is uneconomical but could become an option in addressing water scarcity issues.

LSM low-emission policies can contribute to emission reductions but they lead to increased costs. Local resource utilization policies are cost-efficient and environmentally inefficient and should thus be avoided. However, municipalities must set clear energy and resource utilization goals when adopting LSM business models and bear costs to reach municipal environmental goals. As no specific local limitations or constraints in the municipality occurred, the modeling approach can also be applied to municipalities with similar scope.

5.5. Nomenclature

Sets

$\mathcal{C}$	LSCs	index: i
$\mathcal{J}$	Sectors	index: j
$\mathcal{M}$	LSM positions	index: m
$\mathcal{E}$	External sources	index: k
$\mathcal{T}$	Available technologies	index: l
T	Total timesteps	index: t

Parameters

$WACC$	Weighted average cost of capital	%
N	Amortization period	-
$C^{\mathrm{inv,var}}$	Capacity-based share of investment costs	€ per [*technology*]
$C^{\mathrm{inv,fix}}$	Fixed share of investment costs	€
$C^{\mathrm{o\&M}}$	Operational costs	€ per [*technology*]
$N^{\mathrm{household}}$	Number of households per LSC	-
D_j	Demand or accruing resource per sector	[*sector*]
$V^{\mathrm{greywater,unit}}$	Maximum volume of one greywater system	m^3
F^{CO2}	Emission factor	t per [*technology*]
T^{cluster}	Number of time steps in clustering step	-
T^{year}	Number of time steps in operational step	-
F^{year}	Factor for shorter optimization period	-
Π^{procure}	Price for external procurement	€ per [*source*]
Π^{feedin}	External feedin tariff	€ per [*source*]
Π^{elec2LSM}	Electricity LSM sale tariff	€ per kWh
Π^{LSM2elec}	Price LSM electricity procurement	€ per kWh
Π^{CO2}	$\mathrm{CO_2}$ price	€per t
H_S^{waste}	Heating value waste	kWh/kg
$M_{waste,max}^{\mathrm{trans}}$	Transport capacity waste	kg

Variables

c^{tot}	Total costs	€
c_{step1}^{inv}	Investment costs step 1	€
$c_{step2}^{\mathrm{operational}}$	Operational costs step 2	€
α	Annuity factor	-
x^{max}	Technology capacity investment	[*technology*]
bin^{install}	Binary variable technology investment	-
x_l	Technology flow	[*technology*]
x_k	External source flow	[*source*]
$c^{\mathrm{inv,var}}$	Variable investment costs	€
$c^{\mathrm{inv,fix}}$	Fixed investment costs	€
$c^{\mathrm{O\&M}}$	Operational costs	€
c^{procure}	External procurement costs	€
rev^{feedin}	External feedin revenues	€

em^{CO2}	CO_2 emissions	t
c^{CO2}	Emission costs	€
m^{sludge}	Sludge to waste	kg
$m^{\mathrm{wastetrans,in}}$	Waste transported input	kg
$m^{\mathrm{wastetrans,out}}$	Waste transported output	kg
$m^{\mathrm{waste}}_{comb}$	Incinerated waste	kg
m^{waste}_{AD}	Digested waste	kg
q^{gas}_{AD}	Generated biogas	kWh
m_{disp}	Externally disposed waste	kg
m_{red}	Reduced waste	kg
$int^{\mathrm{greywater}}$	Installed greywater systems	-
$v_{greywater}$	Volume greywater systems	m^3
$v_{waterpipe}$	Pipeline procured water	m^3
v_{sewage}	Accruing sewage	m^3
$v_{sewagetreat}$	Treated sewage	m^3
$v^{\mathrm{water}}_{sewage}$	Recovered water	m^3
$v^{\mathrm{trans,in}}_{sewage}$	Transmitted sewage input	m^3
$v^{\mathrm{trans,out}}_{sewage}$	Transmitted sewage output	m^3
q^{elec2LSM}	Electricity sold to LSM	kWh
rev^{elec2LSM}	Revenues electricity to LSM	€
q^{LSM2elec}	Electricity procured from LSM	kWh
c^{LSM2elec}	Costs electricity procurement from LSM	€
η^{LSM2elec}	Efficiency LSM electricity procurement	-
q_{PV}	PV generation input	kWh
$q^{\mathrm{procure}}_{elgrid}$	Electricity grid procurement	kWh
q^{in}_{bat}	Battery input	kWh
q^{out}_{bat}	Battery output	kWh
q^{elec}_{HP}	Electricity heat pump	kWh
q^{heat}_{HP}	Heat generation heat pump	kWh
$q^{\mathrm{feedin}}_{elgrid}$	Electricity grid procurement	kWh
q^{elec}_{comb}	Waste combustion electricity	kWh
$\eta^{\mathrm{elec}}_{comb}$	Electric efficiency waste combustion	-
q^{heat}_{comb}	Waste combustion heat	kWh
$\eta^{\mathrm{heat}}_{comb}$	Thermal efficiency waste combustion	-
em_{comb}	Emissions waste combustion	t
$share^{\mathrm{usable}}_{comb}$	Usable energy recovery combustion	-

$share^{\text{biodegradable}}$	Share biodegradable waste	-
$bin^{\text{wastetrans,out}}$	Binary transport variable	[0,1]
q_{CHP}^{elec}	Gas CHP electricity	kWh
q_{CHP}^{heat}	Gas CHP heat	kWh
q_{sewage}^{elec}	Electricity demand sewage treatment	kWh
q^{LSM2heat}	LSM heat procurement	kWh
η^{LSM2elec}	Efficiency LSM heat procurement	-
$q_{exhaustheat}$	Exhaust heat	kWh
$q_{gassale}$	Sold gas at market	kWh
$d_{el,total}$	Total variable electricity demand	kWh
$\sigma^{nonLocal}$	Non local energy and resource use	-

Table 5.6.: Model parameters and decision variables

6. Sustainable Development Goals indicator establishment and policy impact on targets

This chapter extends the analyses on LSCs in Section 4 and LSMs in Section 5 to specific indications of the UN SDG. The chapter is based on methodology and results in Maldet et al. (2023a). Therefore, it introduces a UN SDG indicator system that is applied to the LSC in Waihofen/Ybbs and to the LSM in Breitenau am Steinfeld.

The 17 UN SDG provide a roadmap for the global implementation of sustainable development. The UN 2030 agenda further describes communities and local authorities as significant actors in implementing sustainable development (United Nations, 2023b). Therefore, this work focuses on the application of UN SDG indicators in communities and municipalities, intending to provide policy incentives for local sustainable development. The UN SDG consist of goals that depend on social setups but also of plans that sustainable operations and technology introduction can achieve. This work focuses on the six energy and resource-related SDG and their interaction with community and municipality operations and investments.

The UN 2030 agenda includes 169 potential actions for SDG contribution. Furthermore, much research focuses on SDG contribution and implementation. However, the majority proposes large sets of indicators and possible actions, leading to high complexity in the application. Therefore, this work introduces an easily applicable indicator system for the energy- and resource-related SDGs. Each SDG is represented by one percentual value to make the indicators simple and comparable. The SDG indicator definition is performed based on a literature review of currently existing indicators. These are analyzed and adapted for a simple application in communities and municipalities. The developed indicators are applied to an existing community and municipality in Austria by developing an optimization model. These analyses focus on the interaction between community and municipality technology investment and SDG contribution. Moreover, the studies include SDG impact assessments of different policy actions. Finally, the applicability and policy impacts of the proposed SDG indicators for communities and municipalities are compared. Figure 6.1 presents the workflow in the paper.

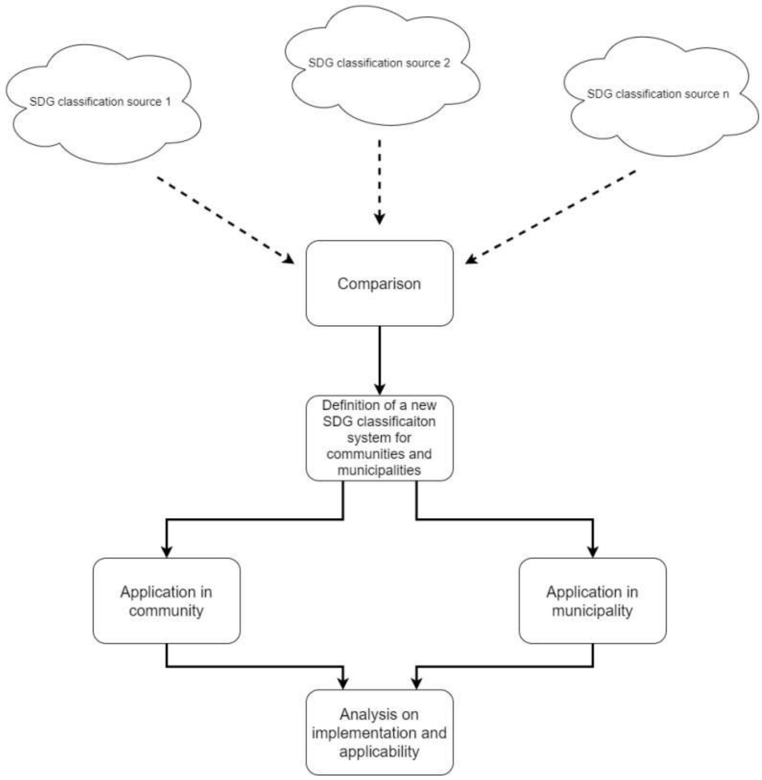

Figure 6.1.: SDG indicator establishment and community/municipality application

The core objectives of the analyses are to define an easily applicable SDG indicator system that provides incentives for technology investments and sustainable operations and to determine policy implications based on the indicators that can further promote sustainable development. The proposed SDG indicator system and different policy actions are applied in the community presented in Section 4 and the municipality presented in Section 5.

Section 6.1 introduces the method for defining the proposed UN SDG indicator system and the indicator application in case studies. Furthermore, Section 6.2 presents the community and municipality analyses of the indicator applications. Section 6.3 discusses the introduction of the indicators and the impact of UN SDG incentive schemes. Finally, Section 6.4 concludes the chapter with a resumé of the significant outcomes.

6.1. Methods

This section provides an overview of existing SDG indicator systems and proposes a new SDG indicator system applicable to communities and municipalities in Section 6.1.1. Furthermore, Section 6.1.2 presents the method that is applied in community and municipality case studies.

6.1.1. Introduction of an UN SDG indicator system

Communal sustainable development analyses have in common that they focus on SDG contribution. However, no clear indicators or targets are defined. Therefore, this section focuses on SDG quantification. The primary focus is set on energy- and resource-related SDGs. This Section extends the analyzed UN SDG indicators in Section 2.3.3.

Tables 6.1 and 6.2 present an overview of the energy- and resource-related SDG indicators that are proposed by the United Nations (2023b), ISO (2018), OECD Council (2017) and Jossin and Peters (2022). In the comparison, identified relevant indicators in the proposed systems are considered.

Table 6.1.: Comparison of different proposed sustainable development indicators, SDG 1, 6 and 7

SDG	UN indicators	ISO 37120	OECD	Jossin and Peters
1: No poverty	Proportion of population below poverty level	Percentage of population living in poverty	Poverty rate	Gini coefficient
6: Clean water and sanitation	Degree of integrated water resources management, proportion of wastewater flows	Percentage of population with potable water supply and wastewater treatment	Share of population without wastewater collection	Drinking water consumption, percentage of treated wastewater
7: Affordable and clean energy	Renewable energy share in final energy consumption	Percentage of energy derived from renewable sources	Renewable electricity share in electricity generation	Renewable energy in energy consumption, municipal investment in development

Table 6.2.: Comparison of different proposed sustainable development indicators, SDG 11, 12 and 13

SDG	UN indicators	ISO 37120	OECD	Jossin and Peters
11: Sustainable cities and communities	Proportion of solid waste managed	ISO 37120 is established for sustainable city and community indication	Municipal waste generated	Combination of multiple categories including energy and resources
12: Responsible consumption and production	National recycling rate, installed renewable energy generation capacities	Number of recycled waste, reduced waste or landfilled waste	Recycling rate of municipal waste	Drinking water consumption, energy consumption, waste generation, recycling rate
13: Climate action	Total GHG emissions per year	Total GHG emissions per capita	Production based CO_2 emissions	CO_2 emissions in private household and municipal facilities

The proposed indicator systems in Tables 6.1 and 6.2 show differences in particular SDG targets. SDG11 can be widely interpreted, which can be seen as the sources considered waste management and multiple other energy- and resource-related indicators. SDG12 is also not strictly limited to waste by all sources. Moreover, different indicators for the different SDGs are not comparable to each other, making an overall comparable indicator system hardly applicable. Therefore, this paper proposes an adaptation of the proposed indicators in Tables 6.1 and 6.2 to a newly-defined SDG indicator system. The indicator system is designed to be applicable in sustainable communities and cities, especially for application in Austria. However, different indicators for both communities and municipalities are implemented because of their different scopes. Furthermore, to make the indicators comparable, each indicator is defined as a percentual value. A higher value indicates better contribution to a particular SDG. The goal is to implement an easily applicable SDG indicator system that reflects sustainable development contribution and provides appropriate incentives.

SDG1 (no poverty) $i^{\text{nopoverty}_{\text{SDG1}}}$ is equally indicated in communities and municipalities. It is defined as the cost reduction that can be achieved by sustainable technology implementation. For providing an SDG1 indicator, total cost improvement c^{tot} compared with Business as usual (BaU) costs $c^{\text{tot,BaU}}$, for the same community or municipality without sustainable technology installation are considered. This benchmark is required to provide a percentual value for the indicator. The target is described in Equation 6.1.

$$i^{\text{nopoverty}_{\text{SDG1}}} = \frac{c^{\text{tot,BaU}} - c^{\text{tot}}}{c^{\text{tot,BaU}}} \tag{6.1}$$

SDG6 (clean water and sanitation) $i_{com}^{\text{cleanwater}_{\text{SDG6}}}$ is indicated differently in communities and municipalities. Communities (see Equation 6.2) consider the amount of reduced $v_{water}^{\text{reduced}}$ and reused water in the form of greywater $v_{water,com}^{\text{greywater}}$ in relation to the total water demand $D_{water,com}$.

$$i_{com}^{\text{cleanwater}_{\text{SDG6}}} = \frac{v_{water,com}^{\text{reduced}} + v_{water,com}^{\text{greywater}}}{D_{water,com}} \tag{6.2}$$

The SDG6 indicator for municipalities $i_{mun}^{\text{cleanwater}_{\text{SDG6}}}$ extends the enumerator to recovered water from sewage treatment $v_{water,mun}^{\text{recovered}}$, which can be used for water demand coverage. Equation 6.3 presents the indicator.

$$i_{mun}^{\text{cleanwater}_{\text{SDG6}}} = \frac{v_{water,mun}^{\text{reduced}} + v_{water,mun}^{\text{greywater}} + v_{water,mun}^{\text{recovered}}}{D_{water,mun}} \tag{6.3}$$

The SDG7 (clean and affordable energy) indicator is also implemented differently in communities and municipalities. The indicator $i_{com}^{\text{cleanenergy}_{\text{SDG7}}}$ considers the share of renewable energy procurement $q_{el,com}^{\text{ren}}$, in relation to the total energy procurement $q_{el,com}^{\text{tot}}$. Energy procurement includes PV generation $q_{el,com}^{\text{PV}}$, electricity grid procurement $q_{el,com}^{\text{elgrid}}$, heat pump heat generation $q_{heat,com}^{\text{HP}}$ and district heat procurement $q_{heat,com}^{\text{dhgrid}}$. For the renewable share of grid procurement, the percentage of renewable energy in the electricity F_{elgrid}^{ren} and heat mix F_{dhgrid}^{ren} are considered. Moreover, electricity feed-in $q_{el,com}^{\text{feedin}}$ is subtracted in the enumerator to consider efficient energy utilization and to facilitate the local use of renewable energy. Equations 6.4 to 6.6 present the indicator for communities.

$$\begin{aligned} q_{en,com}^{\text{ren}} = q_{el,com}^{\text{PV}} &+ F_{elgrid}^{\text{ren}} \cdot q_{el,com}^{\text{elgrid}} + q_{heat,com}^{\text{HP}} \\ &+ F_{dhgrid}^{\text{ren}} \cdot q_{heat,com}^{\text{dhgrid}} - q_{el,com}^{\text{feedin}} \end{aligned} \tag{6.4}$$

$$q_{en,com}^{\text{tot}} = q_{el,com}^{\text{PV}} + q_{el,com}^{\text{elgrid}} + q_{heat,com}^{\text{HP}} + q_{heat,com}^{\text{dhgrid}} \tag{6.5}$$

$$i_{com}^{\text{cleanenergy}_{\text{SDG7}}} = \frac{q_{en,com}^{\text{ren}}}{q_{en,com}^{\text{tot}}} \tag{6.6}$$

Municipal SDG7 indicators $i_{mun}^{\text{cleanenergy}_{\text{SDG7}}}$ additionally consider recovered electricity $q_{el,mun}^{\text{wastecomb}}$ and heat $q_{el,mun}^{\text{wastecomb}}$ from waste incineration (see Equations 6.7 to 6.9). However, in the enumerator, only the biogenic share of waste $F_{waste}^{\text{biogene}}$ is counted as renewable. Furthermore, exhaust heat $q_{heat,mun}^{\text{exhaust}}$ is considered in the enumerator to efficiently utilize locally generated heat in municipalities.

$$\begin{aligned} q_{en,mun}^{\text{ren}} = q_{el,mun}^{\text{PV}} + F_{elgrid}^{\text{ren}} \cdot q_{el,mun}^{\text{elgrid}} + q_{heat,mun}^{\text{HP}} \\ + F_{dhgrid}^{\text{ren}} \cdot q_{heat,mun}^{\text{dhgrid}} - q_{el,mun}^{\text{feedin}} \\ + F_{waste}^{\text{biogene}} \cdot (q_{el,mun}^{\text{wastecomb}} + q_{heat,mun}^{\text{wastecomb}}) - q_{heat,mun}^{\text{exhaust}} \end{aligned} \tag{6.7}$$

$$\begin{aligned} q_{en,mun}^{\text{tot}} = q_{el,mun}^{\text{PV}} + q_{el,mun}^{\text{elgrid}} + q_{heat,mun}^{\text{HP}} + q_{heat,mun}^{\text{dhgrid}} \\ + q_{el,mun}^{\text{wastecomb}} + q_{heat,mun}^{\text{wastecomb}} \end{aligned} \tag{6.8}$$

$$i_{mun}^{\text{cleanenergy}_{\text{SDG7}}} = \frac{q_{en,mun}^{\text{ren}}}{q_{en,mun}^{\text{tot}}} \tag{6.9}$$

SDG11 is not represented by a single indicator, but rather considers a combination of all other energy- and resource-related indicators. The concept of communities and municipalities applying an SDG indicator system is automatically a contribution to SDG11. Each indicator is weighted by its contributions, compared to the overall contribution (see Equation 6.10). All weighted indicator contributions sum up to 100 %, as presented in Equation 6.11.

$$i_{new}^{\text{SDG,k}} = \frac{i_{old}^{\text{SDG,k}}}{\sum_{j \in SDGs} i_{old}^{\text{SDG,j}}} \quad \forall k \in \mathcal{SDG} \tag{6.10}$$

$$\sum_{k \in \mathcal{SDG}} i_{new}^{\text{SDG,k}} = 100\% \tag{6.11}$$

SDG12 is indicated equally in communities and municipalities by $i^{\mathrm{consprod}_{\mathrm{SDG12}}}$. The indicator considers the ratio of reduced and recycled waste to the total accruing waste, as presented in Equation 6.12.

$$i^{\mathrm{consprod}_{\mathrm{SDG12}}} = \frac{m_{waste}^{\mathrm{recycled}} + m_{waste}^{\mathrm{reduced}}}{M_{waste}^{\mathrm{total}}} \tag{6.12}$$

Finally, the SDG13 indicator $i^{\mathrm{climateactionSDG13}}$ considers the emissions em^{tot} compared with the BaU scenario emissions $em^{\mathrm{tot,BaU}}$ of the community or municipality, similar to SDG1 (see Equation 6.13).

$$i^{\mathrm{climateaction}_{\mathrm{SDG13}}} = \frac{em^{\mathrm{tot,BaU}} - em^{\mathrm{tot}}}{em^{\mathrm{tot,BaU}}} \tag{6.13}$$

The paper considers the proposed indicators for further analyses and discussions. Table 6.3 summarizes the developed SDG indicators.

6.1.2. Case studies, materials and methods

The method is applied in the case studies for the community and municipality. The case study parameters are summarized in the Appendix. Both, communities and municipalities, are analyzed by optimization models, representing the energy- and resource-related operations and investments in the systems. Therefore, the optimization modeling framework "Resource Utilization in Sector Coupling" (RUTIS) (Maldet, 2022) is extended to particular SDG target achievement functionalities. A validation of the model is also presented in Maldet et al., 2022b. The model implements a cost minimization, represented in Equation 6.14.

$$min(z) = min(c^{\mathrm{tot}}) = min(c^{\mathrm{procurement}} + c^{\mathrm{operational}} + c^{\mathrm{invest}}) \tag{6.14}$$

Table 6.3.: Proposed SDG contribution indicators for communities and municipalities

SDG	Community indicator	Municipality indicator
1: No poverty	Community cost reduction compared to BaU in % (Equation 6.1)	Municipality cost reduction compared to BaU in % (Equation 6.1)
6: Clean water and sanitation	Percentage of reduced water and reused greywater in relation to community water demand (Equation 6.2)	Percentage of reduced water, reused greywater and recovered water from sewage treatment in relation to municipality water demand (Equation 6.3)
7: Affordable and clean energy	Community share of renewable energy generation, excluding fed-in energy, in % (Equation 6.6)	Municipality share of renewable energy generation, including the biogenic share of waste incineration and excluding fed-in energy, in % (Equation 6.9)
11: Sustainable cities and communities	Combination impact of other SDGs in communities	Combination impact of other SDGs in municipalities
12: Responsible consumption and production	Community share of reduced and recycled waste to accruing waste (Equation 6.12)	Municipality share of reduced and recycled waste to accruing waste (Equation 6.12)
13: Climate action	Community emission reduction compared to BaU in % (Equation 6.13)	Municipality emission reduction compared to BaU in % (Equation 6.13)

Procurement costs $c^{\text{procurement}}$ represent the costs for external energy or resource procurement and operational costs $c^{\text{operational}}$ represent costs for technology operation. Both are multiplied by the amount of procured or operated energy and resources. Investment costs c^{invest} are considered with annuities α_l, multiplied by the installed technology capacity x_l, whereas the capacity is determined by the optimization. Annuities consider the weighted average cost of capital $WACC$ and the amortization period of the technologies N_l Equations 6.15 and 6.16 present the model implementation.

$$\alpha_l = \frac{(1 + WACC)^{\mathrm{N_l}} \cdot WACC}{(1 + WACC)^{\mathrm{N_l}} - 1} \quad \forall l \in \mathcal{T} \tag{6.15}$$

$$c_l^{\text{invest}} = \alpha_l \cdot x_l \cdot C_l^{\text{invest}} \quad \forall l \in \mathcal{T} \tag{6.16}$$

Basic model constraints include conversion relations, technology limitation, balance rules for all sectors and storage equations. Detailed RUTIS model constraint equations are presented in Maldet et al., 2022b.

The case study applies three different policy paths, where various policy actions are applied in the community and municipality. All three policies aim to improve sustainable development and contribution to the UN SDG, whereas the particular policy actions differ depending on the path. Figure 6.2 presents the workflow of the policy paths.

Path 1 represents strict target setting, where particular SDG contribution targets must be strictly achieved by technology installation and sustainable behaviour. Analyses in Path 1 include sensitivity analyses on SDG target achievements, whereas changes in technology portfolios and total costs are examined. Sensitivity analysis for a simultaneous increase in all SDG targets leads to different limits for different SDGs. Thus, if an SDG target is at its limit, the goal is set to the maximum possible value for the following sensitivity values. The SDG targets are implemented as additional model constraints. The dual variables of the constraints are extracted to analyze the impact and costs of the limitations, particularly target achievement. The constraints are derived from the indicator system presented in Table 6.3. However, it must

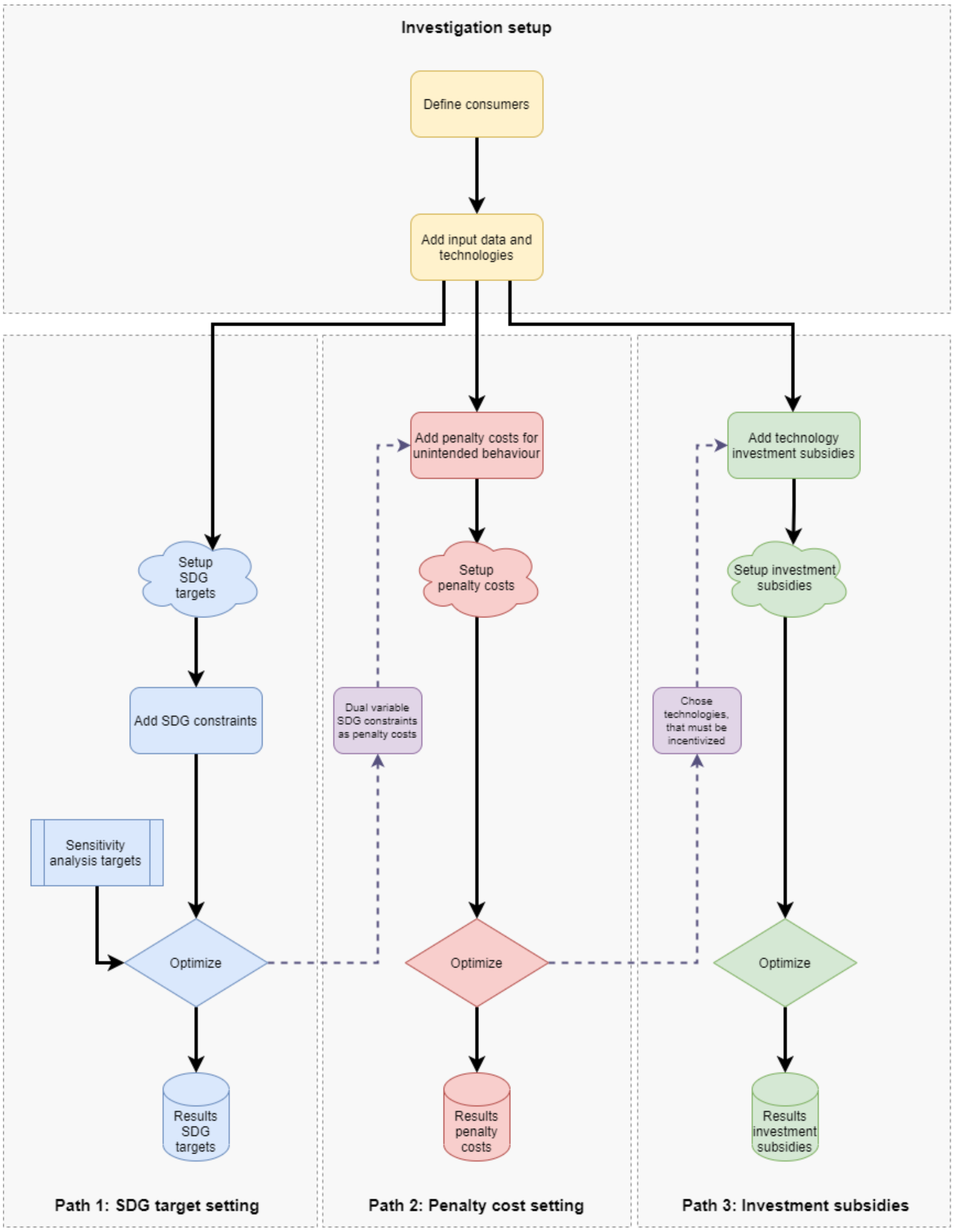

Figure 6.2.: Case study policy paths

be considered that SDG6 and SDG7 indicators are implemented differently in communities and municipalities. Equations 6.17 to 6.22 present the model constraint implementation. TG describes a predefined SDG target and λ represents the dual variables. Terms for water or waste reduction are not implemented in all analyses and can be considered additional sensitivities.

$$\frac{v_{water,com}^{\text{reduced}} + v_{water,com}^{\text{greywater}}}{D_{water,com}} \geq TG_{com}^{\text{cleanwater}_{\text{SDG6}}} \quad : \lambda_{com}^{\text{cleanwater}_{\text{SDG6}}} \tag{6.17}$$

$$\frac{v_{water,mun}^{\text{reduced}} + v_{water,mun}^{\text{greywater}} + v_{water,mun}^{\text{recovered}}}{D_{water,mun}} \geq TG_{mun}^{\text{cleanwater}_{\text{SDG6}}} \quad : \lambda_{mun}^{\text{cleanwater}_{\text{SDG6}}} \tag{6.18}$$

$$\frac{q_{en,com}^{\text{ren}}}{q_{en,com}^{\text{tot}}} \geq TG_{com}^{\text{cleanenergy}_{\text{SDG7}}} \quad : \lambda_{com}^{\text{cleanenergy}_{\text{SDG7}}} \tag{6.19}$$

$$\frac{q_{en,mun}^{\text{ren}}}{q_{en,mun}^{\text{tot}}} \geq TG_{mun}^{\text{cleanenergy}_{\text{SDG7}}} \quad : \lambda_{mun}^{\text{cleanenergy}_{\text{SDG7}}} \tag{6.20}$$

$$\frac{m_{waste}^{\text{recycled}} + m_{waste}^{\text{reduced}}}{M_{waste}^{\text{total}}} \geq TG^{\text{consprod}_{\text{SDG12}}} \quad : \lambda^{\text{consprod}_{\text{SDG12}}} \tag{6.21}$$

$$\frac{em^{\text{tot,BaU}} - em^{\text{tot}}}{em^{\text{tot,BaU}}} \geq TG^{\text{climateaction}_{\text{SDG13}}} \quad : \lambda^{\text{climateaction}_{\text{SDG13}}} \tag{6.22}$$

The policy actions in Path 2 use the dual variables to create penalties for actions leading to lower SDG targets. Moreover, technologies that are installed to avoid penalties can be identified in Path 2. Path 3 considers policy actions in the form of investment subsidies for the recognized technologies. Additional costs in both paths, namely, penalty costs for consumers in Path 2 and subsidy costs for the funding agency in Path 3, are considered within the system boundaries, as subsidies are paid by consumers' taxes. Therefore, for the evaluation, penalties and subsidies are considered cost loads for the consumers. Finally, the aim of the analyses is to compare the three paths in the community and municipality setups.

6.2. Indicator application results

This section shows the application and results of the proposed indicators in communities (Section 6.2.1) and municipalities (Section 6.2.2). It presents investigation setups and results of the analyses in regard with the case study method, that was presented in Section 6.1.2.

6.2.1. Community analyses

The community analyses in this Section present the investigation setup, the results of the studies for target setting (Path 1) and the results for incentive schemes (Path 2 and 3). Additional results of the analyses are presented in the Appendix.

Community investigation setup

The SC GeWoZu (Verein GeWoZu, 2020), consisting of 12 households, is considered for the community analyses. Consumers in the community are aggregated. Figure 6.3 presents the investigation setup in the community.

The model performs investment decisions in PV and batteries in the electricity sector. Excess electricity can be fed into the grid and the remaining demand is covered by electricity grid procurement. The heat sector considers investment decisions in heat pumps and district heat connections, whereas

Figure 6.3.: Case study setup for community analyses

heat can be procured from an external heat source. Potable water is usually procured from pipelines. However, investment decisions in separate greywater systems and sensitivities for water reduction are additionally considered for the water sector. The waste sector includes competition between waste disposal and recycling, which are implemented with different costs. Similar to the water sector, waste reduction is considered as sensitivity.

Politically driven goal achievement in communities

This section presents the results of the analyses for SDG target policy actions (Path 1). First, single SDG contribution target sensitivity analyses are presented, followed by a complete sensitivity analysis on all SDGs.

Without constraints, the total costs can be reduced by 21 % compared to the business-as-usual (BaU) setup because of the financial benefits due to clean technology installation. SDG6 (clean water and sanitation) and SDG12 (responsible consumption and production) are not targeted, whereas SDG7 (clean and affordable energy) and SDG13 (climate action) reach 73 % and 42 %, respectively. Thus, even without particular policy actions, clean technology installation leads to increased SDG7 contributions and to total cost reductions. Figure 6.4 presents the target achievement for the energy- and resource-related SDGs without target achievement constraints. Additionally, it shows the contribution of SDG11 (sustainable cities and communities).

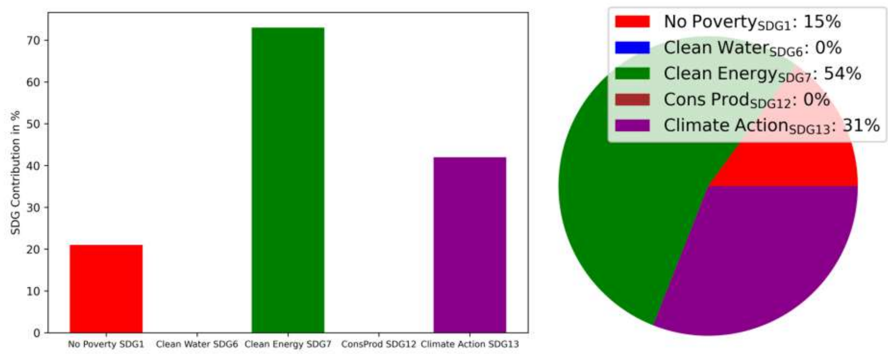

Figure 6.4.: Community contribution to SDGs (left) and share of single SDG contributions to SDG11 (sustainable cities and communities) (right)

Figure 6.5 presents the impact of the sensitivity analysis of SDG6 on the total costs (represented with SDG1) and on the dual variables of SDG6, comparing a conventional setup without options for water reductions and the additional consideration of such.

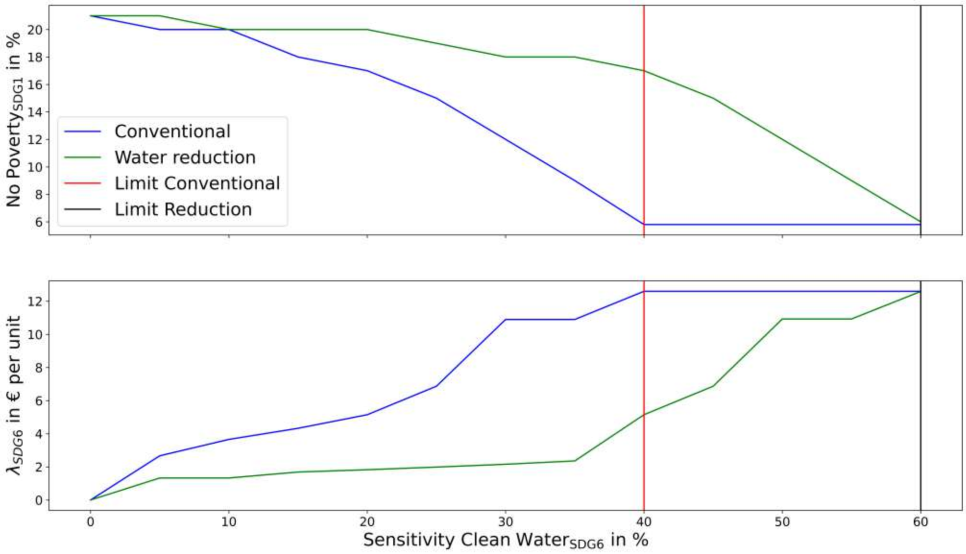

Figure 6.5.: SDG1 - no poverty (top) and the dual variable of SDG6 (clean water and sanitatio)n in dependency of SDG6 contribution targets in the community

A community can only achieve clean water and sanitation (SDG6) improvement by installing greywater systems. However, as the share of greywater in sewage is limited, SDG6 has its limit at 40 %. The high costs for target achievement can be seen in SDG1 decreases and the dual variables. Water reduction of 20 % leads to a linear shift of the limit and dual variable and to lower costs at higher targets. SDG7 (clean and affordable energy) targets can be achieved by favouring heat pump installation to district heat connection, as presented in Figure 6.6. Contributions up to 90 % can be achieved. Moreover, batteries are installed to promote local renewable energy use and to prevent electricity grid feed-in. The dual variables define the costs for additional target achievement. They are low compared to SDG 6. However, target increase from 85 % to 90 % leads to a sharp increase in the dual variables.

Figure 6.7 presents the sensitivity analysis of SDG12 (responsible consumption and production), where additional recycling leads to higher costs. The increase can be lowered by promoting waste reduction.

Finally, Figure 6.8 shows a direct correlation between SDG7 and SDG13 (cli-

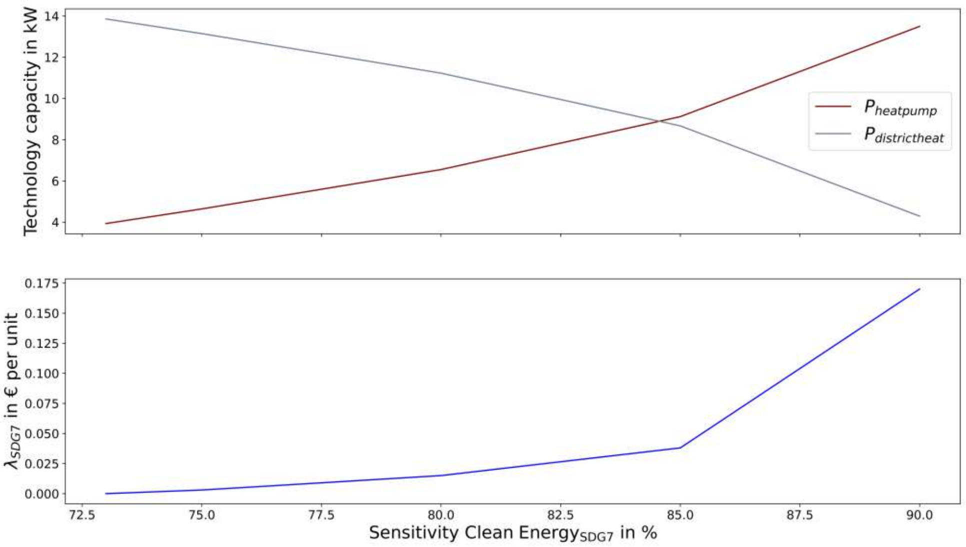

Figure 6.6.: Community heat technology installation (top) and the dual variable of SDG7 (clean and affordable energy) in dependency of SDG7 contribution targets

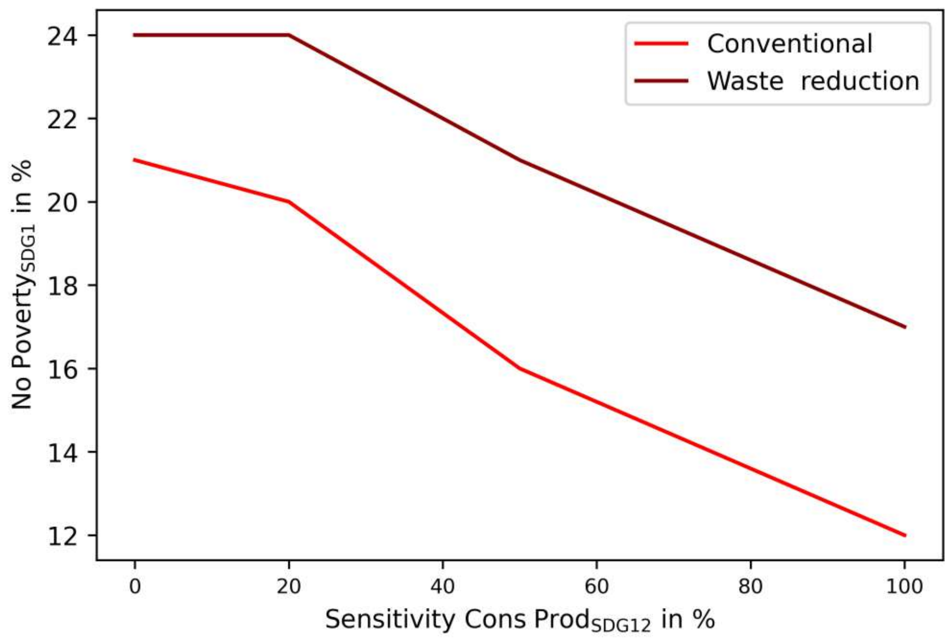

Figure 6.7.: Community sensitivity analysis for SDG12 (responsible consumption and production) with and without waste reduction

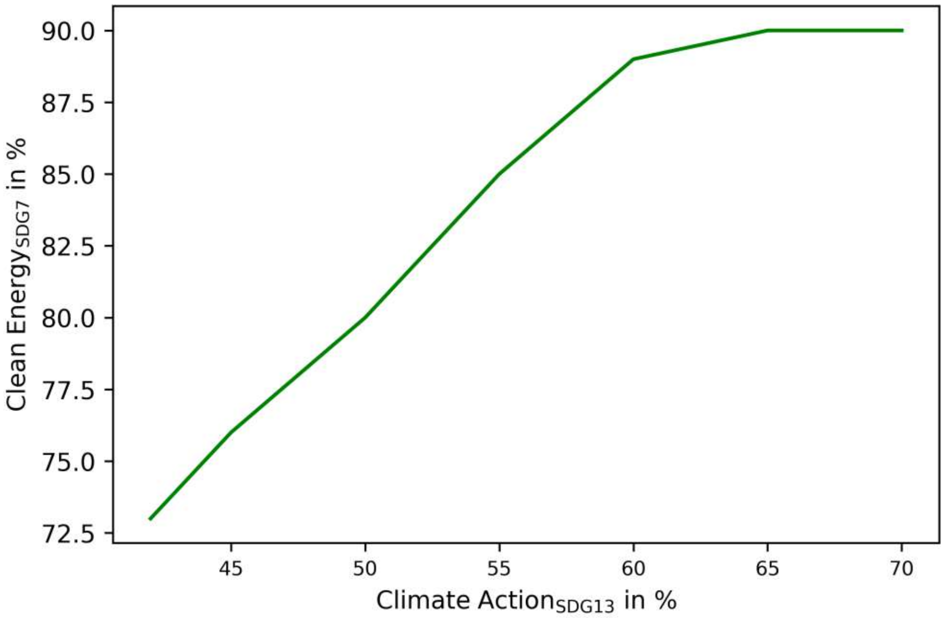

Figure 6.8.: Correlation between SDG13 (climate action) and SDG7 (clean and affordable energy) in communities

mate action). However, at SDG13 contribution targets over 60 %, only SDG7 slightly increases as resource-related operations such as greywater installation and waste recycling are increasingly implemented, which do not directly contribute to SDG7.

The simultaneous sensitivity analysis results show that different SDG targets become active at different limits. According to the Karush-Kuhn-Tucker (KKT) conditions, a constraint and an SDG target become active if the respective dual variables are not equal to zero. SDG6 and SDG12 are the first active constraints at 5 %, followed by SDG13 at 50 %. Owing the correlation with SDG13, SDG7 is the last functional constraint at 90 %. Limits are similar to the single-goal sensitivity analyses, with SDG6 limit at 40 %, SDG13 at 70 %, and SDG7 at 90 %. As no limit for waste recycling was assumed, the constraint is not limited in target setting. Detailed results of the simultaneous sensitivity analysis are presented in the Appendix.

Politically driven incentive schemes in communities

This section presents the results of the incentive schemes in the form of penalties (Path 2) and investment subsidies (Path 3). Detailed results on Path 2 and Path 3 analyses are presented in the Appendix. Incentive schemes in Paths 2 and 3 both lead to the same SDG contributions as predefined targets in Path 1. However, the incentive schemes differ in their impact on the total costs and in cost-requirement for penalizing or providing incentives. Table 6.4 presents a comparison between different incentive schemes.

SDG6 improvement leads to the highest incentive costs. Greywater installation requires 20 % of incentive costs of sewage disposal penalties. The relations differ in SDG7, where penalties for district heat procurement lead to lower incentive costs than heat pump investment subsidies. SDG12 incentives are independent of the implementation. Waste disposal penalties automatically prevent disposal, leading to higher costs for consumers. SDG13 improvement requires comparably high costs. Considering a combination of incentive schemes leads to higher incentive costs for penalties compared with investment subsidies. However, a combination of both, penalties and subsidies, leads to the lowest incentive costs.

6.2.2. Municipality analyses

This section presents the municipality setup, the SDG target setting of the municipality and incentive schemes for the municipality.

Municipality investigation setup

The analyses are performed in the municipality Breitenau am Steinfeld (Gemeinde Breitenau, 2023), Lower Austria, consisting of 730 households that are aggregated. Figure 6.9 presents the technologies and operations considered in the municipality. Compared to the community, municipal analyses

Table 6.4.: Comparison of policy paths 2 and 3 regarding incentive cost volume, total community costs and cost increases in the community

Policy	**Incentive**	**Incentive costs in €**	**Total community costs in €**	**Cost increase in %**
No incentives	-	0	18723	0
Sewage disposal penalty	10.9 €/m^3	10064	20701	10.57
Greywater incentive	400 €/l	2020	20464	9.30
District heat procurement penalty	0.038 €/kWh	194	18979	1.37
Heat pump subsidies	400 €/kW	506	18875	0.81
Waste disposal penalties	0.15 €/kg	0	20895	11.60
Waste recycling subsidies	0.15 €/kg	2228	20895	11.60
CO_2 price	1.17 €/kg_{CO2}	8001	20413	9.02
CO_2 price	0.07 €/kg_{CO2}	697	18771	0.26
Combination penalties	-	10650	23184	23.83
Combination subsidies	-	5311	23811	27.17
Combination half subsidies, half penalties	-	3011	23161	23.70

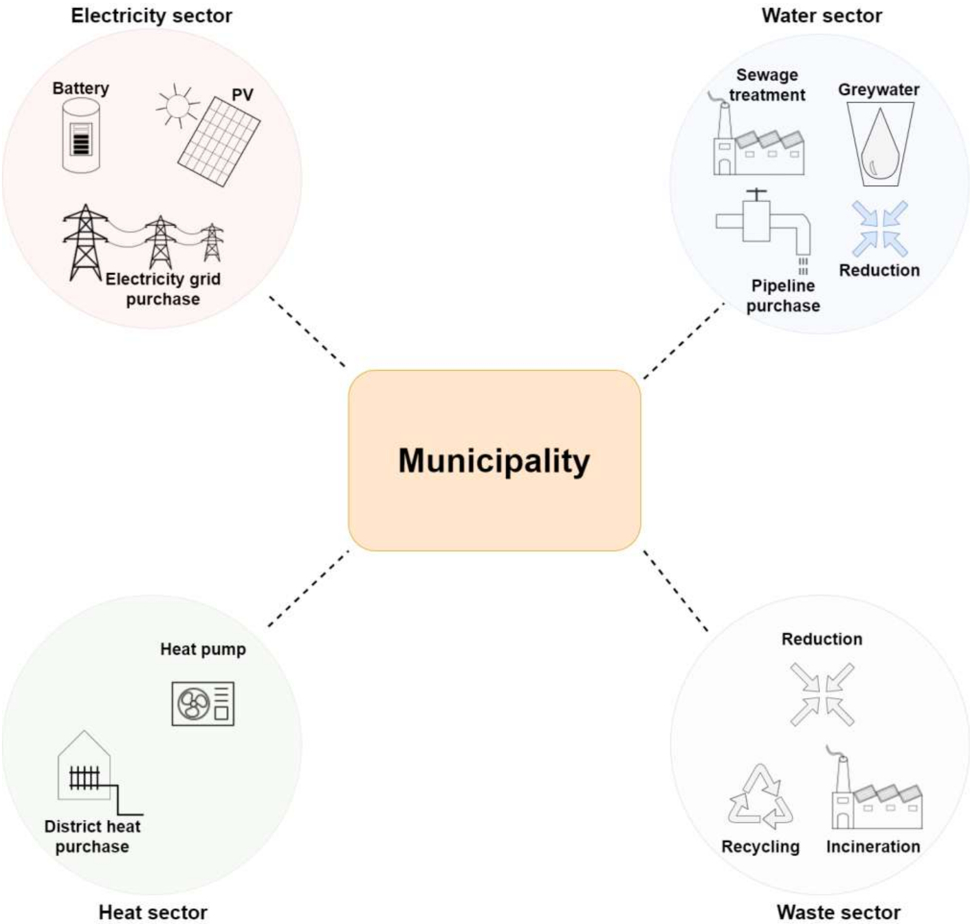

Figure 6.9.: Case study setup for municipality analyses

additionally consider recovered water from sewage treatment and recovered electricity and heat from waste incineration.

The analyses are similar to community analyses, with a significant difference in technology potential and demand scope. Another important change compared with the community is that investment decisions in sewage treatment plants and waste incineration plants are performed instead of resource disposal. Recovered water from sewage treatment and recovered electricity and heat from waste incineration can be used within the municipality and can contribute to SDG target achievement.

Politically driven goal achievement in municipalities

This section presents the results of the SDG contribution target sensitivity analyses (Path 1) for the municipality. Detailed results of the simultaneous SDG sensitivity analyses are presented in the Appendix.

Figure 6.10 shows that unlike for the municipality, SDG6 contribution is at 48 % without constraints due to recovered water from sewage treatment. SDG7 is at 54 %, SDG13 is at 71 % and SDG12 is not targeted without constraints. High cost reductions can be achieved by utilizing recovered electricity and heat from waste incineration. However, the non-biogenic share of waste limits SDG7 target achievement, as in the municipal SDG7 indicator denominator, the total share of recovered energy from waste incineration (biogenic and non-biogenic) is considered.

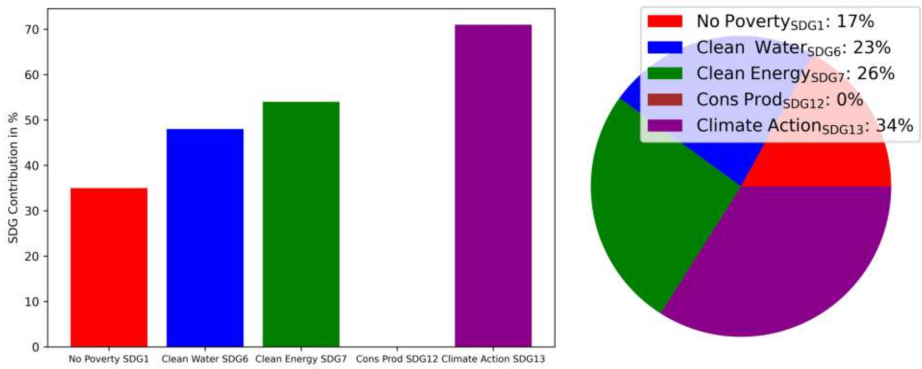

Figure 6.10.: Municipality contribution to SDGs (left) and share of single SDG contributions to SDG11 (sustainable cities and communities) (right)

Figure 6.11 presents the sensitivity analysis for SDG6 (clean water and sanitation) in the municipality.

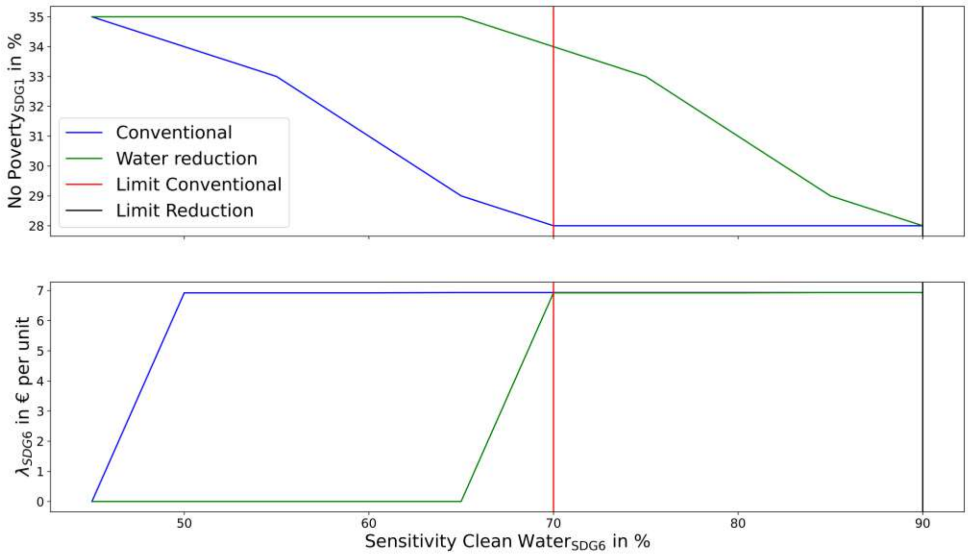

Figure 6.11.: SDG1 - no poverty (top) and the dual variable of SDG6 (clean water and sanitation) in dependency of SDG6 contribution targets in the municipality

The limit for SDG6 is at 70 % and can be improved to 90 % with additional water reduction. The dual variables increase to a constant value when greywater is needed at targets of 20 % and an almost linear cost increase emerges with additional greywater requirements. Similar to the community, heat pump installation increases with higher goals for SDG7 (clean and affordable energy) and batteries are installed for higher local clean energy use. Moreover, PV installation decreases at higher target settings to prevent electricity feed-in, as owing to waste incineration energy recovery, an already high amount of excess electricity exists in the municipality. Figure 6.12 presents the SDG7 sensitivity analysis.

Figure 6.13 presents the sensitivity analysis on SDG12 (responsible consumption and production), where similar increasing costs with increasing waste recycling can be examined. SDG13 (climate action) and SDG7 correlate linearly, as presented in Figure 6.14. Unlike in communities, no saturation emerges. The KKT constraints can identify active SDG constraints in the municipality. Similar to the community, SDG12 becomes active at 5 % and SDG6 becomes active at 50 % because of the implemented sewage treatment

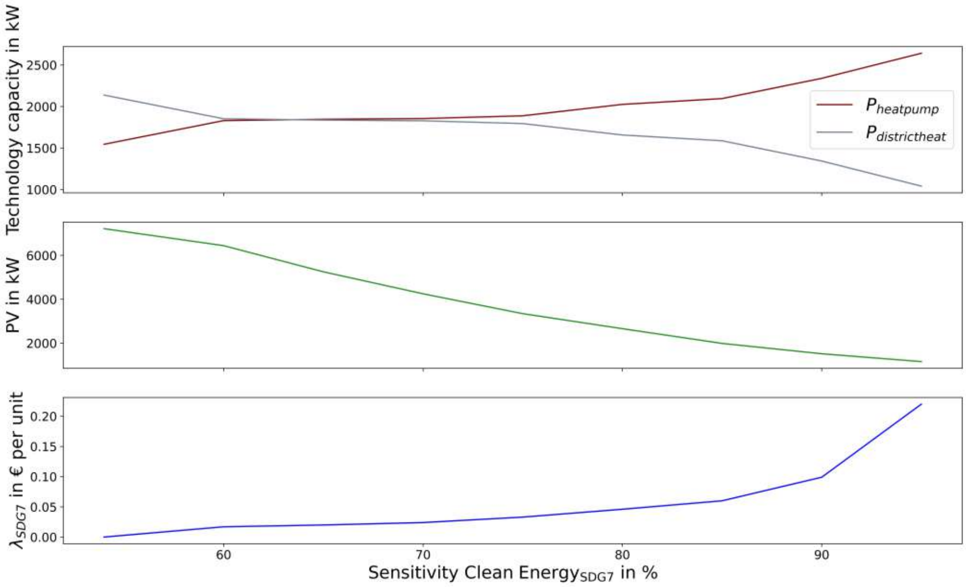

Figure 6.12.: Municipality heat technology installation (top) and the dual variable (bottom) of SDG7 (clean and affordable energy) in dependency of SDG7 contribution targets

water recovery. SDG7 becomes active at 60 %, followed by SDG13 at 85 %. SDG6 reaches the limit at 70 %; SDG13 at 90 %; and SDG7 at 95 %. SDG12 is not limited because of the assumption of unlimited recycling programs.

Politically driven incentive schemes in municipalities

This section presents the results of municipal incentive schemes, whereas detailed analyses are presented in the Appendix. Similar to the community analyses, both incentive schemes lead to the same results as SDG target policies. Table 6.5 presents the applied incentive schemes in the municipality. For single SDG investment schemes, penalties and subsidies have a similar relation as in communities. However, for multiple SDG incentives, the allocation changes, as subsidies lead to higher incentive costs than penalties. As in the previous analysis of communities, combining both incentive schemes results in the lowest costs.

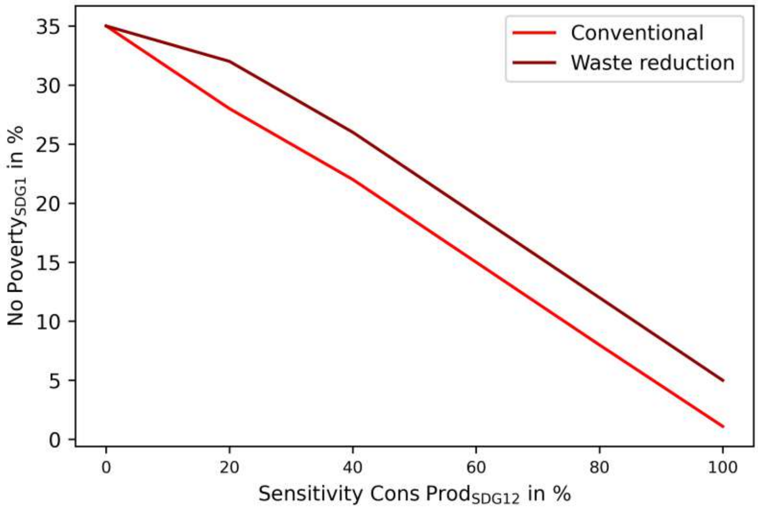

Figure 6.13.: Municipality sensitivity analysis for SDG12 (responsible consumption and production) with and without waste reduction

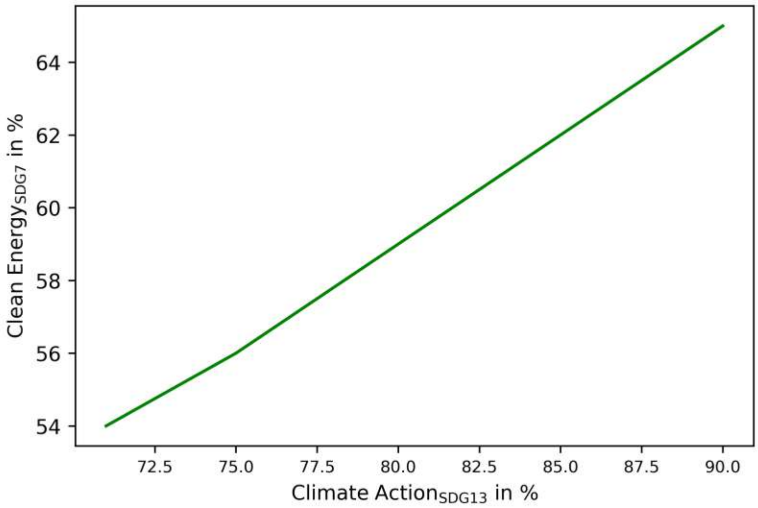

Figure 6.14.: Correlation between SDG13 (climate action) and SDG7 (clean and affordable energy) in municipalities

Table 6.5.: Comparison of policy paths 2 and 3 regarding incentive cost volume, total community costs and cost increases in the municipality

Policy	Incentive	Incentive costs in k€	Total community costs in k€	Cost increase in %
No incentives	-	0	1047	0
Sewage treatment penalty	6.92 €/m^3	244	1169	11.60
Greywater incentive	400 €/l	134	1169	11.64
District heat procurement penalty	0.06 €/kWh	28	1084	3.50
Heat pump subsidies	400 €/kW	126	1068	1.98
Waste disposal penalties	0.37 €/kg	0	1592	52.00
Waste recycling subsidies	0.37 €/kg	554	1592	52.00
CO_2 price	3.1 €/kg_{CO2}	594	1476	40.97
CO_2 price	0.1 €/kg_{CO2}	55	1054	0.65
Combination penalties	-	294	1645	57.10
Combination subsidies	-	715	1668	59.30
Combination half subsidies, half penalties	-	154	1600	52.70

6.3. Discussion

This section discusses the significant outcomes of the case study analyses. Section 6.3.1 provides a discussion on the applicability and scope of the proposed indicator system. Section 6.3.2 compares different SDG policy paths and the proposed incentive schemes.

6.3.1. Application of the proposed UN SDG classification system

The results in Sections 6.2.1 and 6.2.2 showed that the application of the SDG indicator system differs between particular SDG to be achieved. Efficient operation and technology installation can influence energy- and resource-related SDGs. However, policymakers must incentivize communities and municipalities to invest in sustainable development. SDG1 (no poverty) and SDG13 (climate action) require comparison setups. In the proposed method, BaU configurations were provided as benchmarks. However, for long-term applicability, it might be more efficient to give community and municipality benchmarks with broader applicability. This can include comparison with communities and municipalities of similar scope, particularly providing an efficiency standard for communities and municipalities as BaU.

The proposed SDG indicators differ slightly between communities and municipalities, leading to more sustainable operations in both. The application of SDG7 (clean and affordable energy) targets automatically leads to SDG13 improvement in both, as presented in Figures 6.8 and 6.14. However, the results showed different implementations and achievable goals in both configurations, as communities and municipalities differ in scope. Communities can improve SDG6 (clean water and sanitation) by greywater system installation. These are not cost-efficient, and would only be installed with the application of SDG6 targets. SDG7 can be improved in communities by decarbonizing heat generation. Municipality analyses introduce water recovery as a direct contribution to SDG6, and waste energy recovery, which SDG7 assessed. The introduction of waste energy recovery leads to a simultaneous improvement and limitation in SDG7 contribution. Recovered water only improves SDG6 and has no counter-effect. Furthermore, Figures 6.5, 6.7, 6.11 and 6.13 show that both, the community and municipality should apply waste and water reduction. This can increase SDG6 and SDG12 (responsible consumption and production) improvement while keeping SDG1 at a higher level.

The application of the proposed indicators requires critical implementation assessment. Figure 6.12 shows that SDG target setting could also affect sustainable technology installation, as PV installation is decreased with higher SDG7 targets in the municipality. Therefore, a critical assessment of the SDG indicator applicability in specific setups might be necessary to avoid counter-effects. This assessment is the responsibility of municipal governments and policymakers, who establish the SDG indicator system. Municipality actions can include cooperation with large electricity consumers or flexibilities that can use the excess electricity. Policy actions can establish an indicator adaptation for the proposed system, where fed-in electricity is not counted or less counted for the indicator. However, a general indicator adaptation is not purposeful, as the impact might be completely different in other configurations with less excess electricity. Therefore, if an indicator adaptation for the municipality is desired, justification must be made by the municipal government.

6.3.2. Comparison of policy paths

The method established three different SDG policy paths for the improvement of sustainable development in the community and municipality. The proposed SDG policy paths introduced in Figure 6.2 all lead to desired SDG contribution targets, whereas the implementation of the paths differs in their applied policy actions. In terms of goal achievement, all three paths lead to the desired SDG goals, but they differ significantly in costs incurred for target achievement. Proposing strict SDG targets in Path 1 increases costs, especially for greywater installation. Therefore, the SDG1 indicator is mandatory for policymakers to have an overview of community or municipality costs. Moreover, the dual variables of the constraints in Path 1, representing the SDG targets, are an efficient means to determine costs for SDG achievement. They can give an insight until which goals the costs do not increase disproportionally high, as it can be seen in Figure 6.8. These dual variables can therefore help in defining penalties for policy Path 2 as they represent the costs for higher SDG target achievements. The results showed that when the operation that lowers the SDG contribution can be identified, dual variables as penalties lead to the desired goal achievement. However, penalties lead to a direct cost increase for consumers in the community or municipality as these penalties must be directly paid by the consumers. Path 3 can provide an alternative, as funding agencies can support communities and municipalities in higher goal achievement through technology investment subsidies. The technologies, that must be subsidized can be identified in Path 2 by analyzing which technologies are increasingly installed to avoid penalty costs. Path 3 also leads to the desired goals, but it leads to a high subsidy load for funding agencies, which consumers indirectly pay in the form of taxes. Thus, comparing incentive schemes according to Paths 2 and 3, as presented in Tables 6.4 and 6.5 is mandatory for policymakers to define such schemes and to identify to lowest costs incurred for higher SDG targets.

Paths 2 and 3 differ in their impact on the incentive scheme costs, depending on the desired SDG contribution targets. SDG6 contribution in the form of greywater installation is not performed without policy incentives. Sewage treatment penalties lead to higher costs than greywater investment subsidies. Therefore, investment subsidies should be prioritized for SDG6. Regarding SDG7, penalties on district heat procurement are more cost-efficient than heat pump investment subsidies. District heat penalties are equivalent to increasing market prices. Thus, incentive schemes to promote heat pumps might not be necessary for the long-term if district heat prices increase because of changes in the market. SDG12 can be improved by either recycling promotion or disposal penalizing. However, recycling promotion might need more information on recycling programs, whereas disposal penalizing might encourage consumers to look for alternative options to disposal, which can include participation in recycling programs. Higher CO_2 prices lead to higher SDG13 contribution. However, SDG13 is also automatically improved with incentive schemes for SDG7. The results showed that SDG7 incentive schemes are more cost-efficient than SDG13 penalties while leading to similar SDG13 contributions. Thus, the promotion of clean energy technologies should be favoured to emission penalizing. Multiple target achievement incentive schemes vary between communities and municipalities, as presented in Table 6.4 and Table 6.5. Thus, a scope-dependency of the incentive schemes could be identified. If only one kind of incentive scheme is established, investment subsidies should be favoured in communities, whereas penalties should be favored in municipalities. However, the results for both, community and municipality, showed that a combination of penalties and investment subsidies leads to the lowest incentive costs while reaching similar SDG contribution targets. Funding agencies can use penalties to finance at least a share of the provided investment subsidies. Penalties or investment subsidies for single SDG targets should be chosen based on the higher cost-efficiency of the respective incentive scheme. Therefore, the incentive scheme's definition must depend on the particular SDG.

6.4. Resumé

SDG contribution can be measured in communities and municipalities by proposing an appropriate indicator system. Applicability and comparability of the indicators require a simple and transparent indication. However, the indicators depend on the scope of the system. Application leads to differences in technology impact, SDG target costs and SDG target limits. Moreover, introducing SDG targets might lead to decreasing renewable technology investment. The SDG7 (clean and affordable energy) indicator considers efficient energy utilization, aiming to prevent excess energy. However, an adaptation of the indicators for specific setups should be considered, if they can justify an efficient excess energy utilization. However, a general adaptation of the SDG7 indicator can be misleading, as only setups with various energy generation technologies might experience this effect.

Furthermore, technology portfolios and investments have a high impact on SDG target achievement. The heat sector significantly impacts the indicators, especially SDG7 and SDG13 (climate action). Increasing heat pump installation in favour of district heat connection has positive contributions to SDG7 and SDG13, while leading to only slightly rising costs. However, sustainable water management, represented by SDG6 (clean water and sanitation), leads to high costs for the community or municipality. The main option for higher goal achievement is a greywater system installation, which leads to high investment costs. Thus, SDG1 (no poverty) must be considered in the indicator system to monitor the financial load of SDG contribution improvement for consumers.

All introduced policy paths lead to the desired SDG contributions and are thus applicable. However, the costs for consumers to achieve targets differ between the paths. A workflow for policymakers can start with establishing desired SDG targets, followed by defining penalties based on SDG target costs and defining investment subsidies based on identified sustainable technologies in the setups. The decision on penalty or subsidy must be performed concerning the single SDGs. Therefore, a critical assessment of all SDG targets to be achieved is mandatory for policymakers.

6.5. Nomenclature

Sets		
$\mathcal{SDG}$	Energy- and resource-related SDG	index: k
$\mathcal{T}$	Available technologies	index: l
Parameters		
$WACC$	Weighted average cost of capital	%
N_l	Amortization period for technologies	-
C_l^{invest}	Capacity-based costs	€/[l]
$D_{water,com}$	Water demand community	m^3
$D_{water,mun}$	Water demand municipality	m^3
F_{elgrid}^{ren}	Share renewables electricity grid	-
F_{dhgrid}^{ren}	Share renewables district heat grid	-
$F_{waste}^{\text{biogene}}$	Share biogenic waste	-
M_{waste}^{total}	Total accruing waste	kg
$TG_{com}^{\text{cleanwater}_{\text{SDG6}}}$	SDG6 target community	-
$TG_{mun}^{\text{cleanwater}_{\text{SDG6}}}$	SDG6 target municipality	-
$TG_{com}^{\text{cleanenergy}_{\text{SDG7}}}$	SDG7 target community	-

$TG^{\text{cleanenergy}_{\text{SDG7}}}_{mun}$	SDG7 target municipality	-
$TG^{\text{consprod}_{\text{SDG12}}}$	SDG12 target	-
$TG^{\text{climateaction}_{\text{SDG13}}}$	SDG13 target	-

Variables

z	Objective	€
c^{tot}	Total costs	€
$c^{\text{tot,BaU}}$	Total costs business-as-usual scenario	€
c^{invest}	Investment costs	€
$c^{\text{operational}}$	Operational costs	€
$c^{\text{procurement}}$	Procurement costs	€
α	Annuity factor	-
x_l	Capacity investment	$[l]$
$v^{\text{reduced}}_{water,com}$	Reduced water community	m^3
$v^{\text{greywater}}_{water,com}$	Reused greywater community	m^3
$v^{\text{reduced}}_{water,mun}$	Reduced water municipality	m^3
$v^{\text{greywater}}_{water,mun}$	Reused greywater municipality	m^3
$v^{\text{recovered}}_{water,mun}$	Recovered water municipality	m^3
$q^{\text{PV}}_{el,com}$	PV generation community	kWh
$q^{\text{elgrid}}_{el,com}$	Electricity grid procurement community	kWh
$q^{\text{HP}}_{heat,com}$	Heat pump heat generation community	kWh
$q^{\text{dhgrid}}_{heat,com}$	District heat grid procurement community	kWh
$q^{\text{feedin}}_{el,com}$	Electricity grid feed-in community	kWh
$q^{\text{PV}}_{el,mun}$	PV generation municipality	kWh
$q^{\text{elgrid}}_{el,mun}$	Electricity grid procurement municipality	kWh
$q^{\text{HP}}_{heat,mun}$	Heat pump heat generation municipality	kWh
$q^{\text{dhgrid}}_{heat,mun}$	District heat grid procurement municipality	kWh
$q^{\text{feedin}}_{el,mun}$	Electricity grid feed-in municipality	kWh
$q^{\text{wastecomb}}_{el,mun}$	Waste treatment recovered electricity municipality	kWh
$q^{\text{wastecomb}}_{heat,mun}$	Waste treatment recovered heat municipality	kWh
$q^{\text{exhaust}}_{heat,mun}$	Exhaust heat municipality	kWh
$m^{\text{recycled}}_{waste}$	Recycled waste	kg
$m^{\text{reduced}}_{waste}$	Reduced waste	kg
em^{tot}	Total CO_2 emissions	kg_{CO2}
$em^{\text{tot,BaU}}$	CO_2 emissions business-as-usual	kg_{CO2}
$q^{\text{ren}}_{en,com}$	Renewable energy community	kWh

$q_{en,com}^{\text{tot}}$	Total energy community	kWh
$q_{en,mun}^{\text{ren}}$	Renewable energy municipality	kWh
$q_{en,mun}^{\text{tot}}$	Total energy municipality	kWh
$i^{\text{nopoverty}_{\text{SDG1}}}$	SDG1 indicator	-
$i_{com}^{\text{cleanwater}_{\text{SDG6}}}$	SDG6 indicator community	-
$i_{mun}^{\text{cleanwater}_{\text{SDG6}}}$	SDG6 indicator municipality	-
$i_{com}^{\text{cleanenergy}_{\text{SDG7}}}$	SDG7 indicator community	-
$i_{mun}^{\text{cleanenergy}_{\text{SDG7}}}$	SDG7 indicator municipality	-
$i^{\text{consprod}_{\text{SDG12}}}$	SDG12 indicator	-
$i^{\text{climateaction}_{\text{SDG13}}}$	SDG13 indicator	-
$i_{old}^{\text{SDG,k}}$	Nonweighted SDG indicator	-
$i_{new}^{\text{SDG,k}}$	Weighted SDG indicator	-
$\lambda_{com}^{\text{cleanwater}_{\text{SDG6}}}$	SDG6 dual variable community	€/[$goal$]
$\lambda_{mun}^{\text{cleanwater}_{\text{SDG6}}}$	SDG6 dual variable municipality	€/[$goal$]
$\lambda_{com}^{\text{cleanenergy}_{\text{SDG7}}}$	SDG7 dual variable community	€/[$goal$]
$\lambda_{mun}^{\text{cleanenergy}_{\text{SDG7}}}$	SDG7 dual variable municipality	€/[$goal$]
$\lambda^{\text{consprod}_{\text{SDG12}}}$	SDG12 dual variable	€/[$goal$]
$\lambda^{\text{climateaction}_{\text{SDG13}}}$	SDG13 dual variable	€/[$goal$]

Table 6.6.: Model parameters and decision variables

7. Discussion and synthesis of results

This chapter presents the synthesis of the main findings of this thesis, based on the results of the previous sections. Section 7.1 provides the relations between the research questions introduced in Section 1.2 and the results in Chapters 3, 4, 5 and 6. Furthermore, Section 7.2 presents the synthesis of the introduced local resource utilization concepts from a system perspective, focusing on opportunities, upscaling and transferability. Finally, Section 7.3 discusses the strength of the presented concepts and modeling approaches and identifies potential limitations of the work.

7.1. Findings referring to the research questions

The results in chapters 3, 4, 5 and 6 provide findings to the research questions in Section 1.2. This section presents the significant findings for each research question.

Research Question 1. *How can resource utilization of waste and water be considered in sector-coupled energy systems, especially in communities?*

The results in Section 3.2.2 indicate significant contributions of recovered energy from waste and sludge incineration processes to the total energy generation. However, the utilization of recovered energy strongly depends on preliminary resource management and treatment, coordinated with the energy demand. Moreover, the results also show high complexity for waste and water integration into sector coupling approaches. The impact of resource utilization depends on multiple aspects, such as technology availability, technology capacity, environmental goals, costs and CO_2 prices. The complex interaction dependency leads to non-linear relationships between resource utilization and other energy system operations. Thus, no globally valid relations are applicable.

Community establishment can be a further option for local resource utilization. The results in Section 4.2.1 showed that business models in local communities can promote resource utilization at the consumer level. Moreover, the results in Section 4.2.2 presented the highest cost decrease by implementing energy recovery business models in local communities. Thus, sector-coupled resource utilization in communities is crucial for the corresponding business model establishment. Furthermore, resource markets, as presented in Section 4.2.3 can reduce the load on local grids and treatment plants and provide cost reductions. Thus, resource utilization in sector coupling should consider not only energy recovery, but also incentives for resource reduction.

Resource utilization in sector coupling does not only affect energy system operation, but also capacity investments, as found in Section 5.2.2. Considering waste and water in sector coupling can lead to different technology investment decisions and prevent investments in other local generation or storage technologies. Moreover, indicator establishment, as presented in Sections 6.2.1 and 6.2.2 can impact resource utilization in the energy system. The introduced UN SDG targets can promote resource efficiency by defining indicator targets. Moreover, resource utilization can lead to higher indicator contributions and thus, to better benchmarks.

Research Question 2. *How can technology and business model implementation promote efficient energy and resource-related operations within a community?*

Business models for local resource utilization can be implemented in various forms. As indicated by the results in Section 4.2.1, trading leads to cost and emission reductions. Consumers without their technologies can benefit from local energy procurement, while prosumers benefit from local excess energy sales to other community participants. Local resource utilization business models can further reduce costs and emissions. However, the implementation of energy recovery in business models requires cooperation with service providers that charge the real costs incurred. Therefore, the full potential of resource utilization business models can only be exploited if all community participants are committed to joint and fair cooperation.

Results in Section 4.2.2 showed that resource utilization services should include joint technology provision, resource treatment energy recovery, water recovery, trading and incentives for resource reduction. The omission of services always leads to increased costs and emissions, as the business models lead to higher technology utilization efficiency and consumer operation efficiency. Resource markets, as introduced in Section 4.2.3 can lead to further resource reduction. Water consumption rights trading leads to increased water efficiency, while the highest demand reductions and thus, also cost reductions are performed by consumers who are willing to achieve reductions. However, this concept still needs agreements between all community participants. Waste markets are only economically feasible at sufficiently high market prices, as they are in competition with waste treatment energy recovery. Furthermore, the results in Section 4.2.4 show that business models can be improved by cooperation with external service providers, such as industrial exhaust heat providers and farming industries as greywater consumers. However, the feasibility of the business models depends on contracts, which can lead to increased costs if these are not set up appropriately.

Business models can also be implemented in the context of investments. Section 5.2.1 showed that business models for joint energy and resource utilization can promote investments, while business models with energy recovery implementation in Section 5.2.2 showed higher benefits from resource treatment investments. Business models for joint use of technologies in combination with indicator application, as in Sections 6.2.1 and 6.2.2 can further encourage consumers for local energy and resource utilization.

Research Question 3. *How can investments in local resource treatment capacities improve municipal energy supply and circular economy?*

The results in Section 5.2.2 indicated circular economy establishment in municipalities by local resource treatment investments. The treatment plant localization depends on energy availability and trading within the municipality. Without trading and energy recovery, the localization of waste treatment plants is at the site with the shortest distance to other positions in the municipality. Therefore, capacity localization is equivalent to resource transport minimization. As sewage is transmitted without further assumed costs in the pipelines, the sewage treatment plant capacity is not exactly specified by the localization. By implementing trading and energy recovery, the investments in sewage and waste treatment capacities are performed at the same municipal location, as recovered energy from waste is directly used in the sewage treatment plant. Furthermore, trading changes the treatment plant position to the site with the lowest local energy generation potential compared to the demand to be covered at the location. Thus, energy availability and utilization impact capacity localization more than transport distance.

Furthermore, the results in Section 5.2.2 showed that waste incineration flexibility (in combination with storable waste) replaces battery flexibility. Therefore, waste treatment can provide additional or alternative flexibility to the energy system by providing a dispatchable energy source. However, various implemented waste treatment options have different impacts on local energy system operations. Without restrictions, waste incineration is the installed treatment technology due to its highest efficiency. Anaerobic digestion increases costs and emissions, as only energy from biodegradable waste can be recovered. However, this technology could be promoted by alternative utilization of non-biodegradable waste in processes, such as recycling.

Section 5.2.3 focused on greywater investments. The results showed that greywater systems are only installed with particular water efficiency targets due to the high installation costs and the competition with sludge treatment energy recovery in sector-coupled systems. However, other benefits can emerge regarding environmental impact, water scarcity and load reduction on sewage and sludge treatment plants. Furthermore, local strategies and targets affect capacity investments, as presented in Section 5.2.4. Coordinated investments can contribute to target achievement, but target setting always leads to more assets than required and thus, to higher costs. Moreover, the establishment of sustainability indicators, as in Sections 6.2.1 and 6.2.2 affects investments similarly to achieve pre-defined targets, while incentive schemes also lead to different investment allocations than indicated by the market.

Research Question 4. *How can energy- and resource-related UN SDG indicators be established and applied in communities and municipalities to promote efficient operations and technology utilizations?*

Section 6.1.1 presented UN SDG indicators that are defined in the existing literature. However, most of the indicators consist of large sets of multiple indicators for each SDG, thus making the indicators complex in their application. Measures for the UN SDG in the form of such indicators must be simple in their evaluation to be applicable in local communities or municipalities. Therefore, the defined UN SDG indicator system in Section 6.1.1 provides a set of measures, where a percentual value for each indicator represents each SDG. Higher percentual values represent higher SDG contributions. The UN SDGs consists of multiple targets, including goals for energy use, resource utilization and environmental impact, and social aspects. Social SDG contributions in communities and municipalities mainly depend on the configuration of the communes. They cannot be improved by efficient communal operation or technology utilization. Therefore, the developed UN SDG indicators focused on energy and resource-related UN SDG as indicators and benchmarks for such can be improved by efficient local energy and resource utilization.

The analyses in Sections 6.2.1 and 6.2.2 applied the proposed indicators in communes, showing applicability in both the community and municipality. Technology portfolios and investments have a high impact on local sustainable development. However, the impact differs in the analyses due to different scopes and available technology capacities in communities and municipalities. Therefore, implementing UN SDG indicators requires a critical configuration assessment to avoid countereffects on sustainable investments. Potential indicator adaptions might be necessary, as discussed in Section 6.3.1.

Furthermore, Sections 6.2.1 and 6.2.2 showed that only some SDGs are targeted without strict goals or incentives. UN SDG targets lead to alternative use of technologies, leading to market interventions but also to more sustainable energy and resource utilization. However, costs for communities and municipalities increase with UN SDG target setting. Incentive schemes can further promote efficient operations and technology utilizations without leading to higher costs for consumers but for the incentive providers. Incentive schemes in the form of penalties for non-sustainable operations or investment subsidies in sustainable technologies are assumed to be paid from the same financial source: penalties directly by consumers and investment subsidies indirectly by taxes. The impacts of both incentive schemes on the UN SDG are similar, but they differ in their costs, depending on the particular targeted SDG. Thus for cost efficiency, the decision of either penalty or subsidy must be performed based on the SDG to be achieved

7.2. Synthesis of the results

The research questions address multiple issues and opportunities for the introduced resource utilization concepts in this thesis. However, it is also crucial to discuss the impact of local resource utilization in sector coupling from the system perspective. Therefore, this section discusses the system impact, beginning with opportunities in Section 7.2.1. Section 7.2.2 addresses the upscaling and transferability of the analyzed concepts.

7.2.1. Opportunities emerging through local resource utilization

Multiple opportunities arise from local resource utilization in sector coupling. The results showed that the efficient use of recovered energy can provide benefits to the energy system by transitioning to a circular economy. In systems with emission-intensive energy generation, waste and sludge incineration processes can lower the total CO_2 emission in the power sector. However, the RED (European Commission, 2023a) proposes to label such processes as non-renewable due to the non-biogenic share of waste in MSW. According to Vähl (2022), waste incineration energy recovery can increase energy security. Furthermore, the results in this thesis indicated flexibility provision by waste incineration if the treatment is managed appropriately. Waste and sludge treatment energy recovery provides a dispatchable energy source, that can provide flexible energy generation. Therefore, independent of the renewable energy label, incineration processes can provide energy system flexibility and energy security, thus they are crucial for current energy systems.

Water scarcity is becoming an increasingly global issue (United Nations, 2023a). The utilization of greywater can provide additional opportunities for wastewater use and prevent the excessive use of potable water. Moreover, this thesis showed that greywater system installation can provide further system opportunities in emission reductions, decreased investments in sewage treatment plants and fewer loads on treatment processes. Therefore, greywater utilization could provide additional system opportunities by transitioning to a circular water economy.

Community establishment can lead to further system opportunities through resource utilization in sector coupling. Conventional ECs do not consider resource utilization. Moreover, sustainable communities usually do not provide business models for consumer encouragement. Therefore, by combining both concepts, additional opportunities can arise. Significant benefits emerge as consumers can gain an advantage from procuring local energy from joint generation technologies, other participants and resource treatment. Furthermore, consumers can generate revenues from resource-efficient behaviour. Increased efficiency can lead to cost reductions for consumers. Prosumers with their own energy generation or conversion technologies can further benefit by selling energy to the community. More opportunities emerge by introducing energy recovery and resource reduction business models in communities. Additionally, external providers can benefit from community participation, as they can provide innovative services or business models to the communities. Opportunities emerge for local industries by providing a local value generation, gaining a positive image and utilization of otherwise wasted energy or resources.

The results in Section 4.2.2 indicated the lowest consumer costs by considering local energy recovery. Furthermore, Section 4.2.3 showed benefits by water reduction agreements. Consumers willing to save water can generate revenues, while others who cannot save water can still procure such. Water consumption rights trading thus decreases the total water consumption while keeping the necessary restrictions low. Moreover, waste recycling markets with generating revenues from waste recycling can provide incentives for other options than waste treatment. However, purchasers must be found on the market and the market price must be sufficiently high, as recycling markets compete with energy recovery from waste treatment. Therefore, market prices must be defined depending on the goal: Reduce the total waste treated or provide recovered energy to the considered system.

Community establishment over municipalities can lead to additional opportunities for efficient local resource utilization in the energy system. However, local market operations in municipalities differ significantly from local community markets. Municipal investments in treatment facilities and the establishment of energy recovery lead to trading between municipal community participants becoming less relevant. Community participants mainly procure the recovered energy, which is assigned to the municipality. Therefore, energy recovery utilization in municipalities leads to a similar implementation to a centralized energy generation provision. The consumers' opportunities for resource utilization in local communities can be best employed by performing trading processes in local communities and procuring locally recovered energy from municipal communities.

Business models and local investments for resource utilization in sector coupling can provide the highest opportunities by establishing central community management. Community operators, introduced in Section 4.1.1, and municipal authorities, presented in Chapter 5, can emerge as such. These operators can establish local community markets and employ business models for efficient operation and resource utilization. Moreover, they can provide and manage the operation of joint generation and conversion technologies. Introducing such operators can reduce complexity in the community by avoiding multiple consumer interactions in the communities due to tradings over the central interface.

Finally, opportunities arise through the contribution of resource utilization in sector coupling to sustainable development according to the UN SDG. Water utilization directly affects SDG6 (clean water and sanitation) and SDG12 (responsible consumption and production). By implementing energy recovery, SDG7 (affordable and clean) energy and SDG13 (climate action) are addressed. The analyses in this thesis indicated a cost reduction by implementing energy recovery from resource treatment. Therefore, energy recovery implementation contributes to SDG1 (no poverty). By establishing local resource utilization in communities, the introduced community concepts address SDG11 (sustainable cities and communities). The opportunities and contributions to the SDGs can be further promoted by indicator introduction. Such indicators can help set SDG targets and encourage sustainable development through strict goals or incentive schemes. Therefore, resource utilization in sector-coupled energy system processes, in combination with the UN SDG, can provide sustainable development beyond energy system improvement.

Figure 7.1 summarizes the opportunities that arise through local resource utilization in the energy system.

7.2.2. Transferability and upscaling of the introduced concepts

This section provides an overview of the transferability and upscaling of the introduced concepts and findings of this thesis. Therefore, it focuses on transferability and upscaling for resource utilization in sector coupling, business models in local communities, local investments and the definition and application of UN SDG indicators.

Sector coupling approaches should be widely implemented due to their cost efficiency in a low-carbon transition (Bernath et al., 2021). Resource utilization can provide further benefits. However, the impact of local resource utilization depends on the configuration of the considered system, making it only transferable with restrictions. Giugliano et al. (2011) highlighted that energy recovery leads to higher energetic and environmental impact than waste management. Therefore, the transferability of energy recovery concepts is crucial. Transferability of the introduced energy recovery concepts

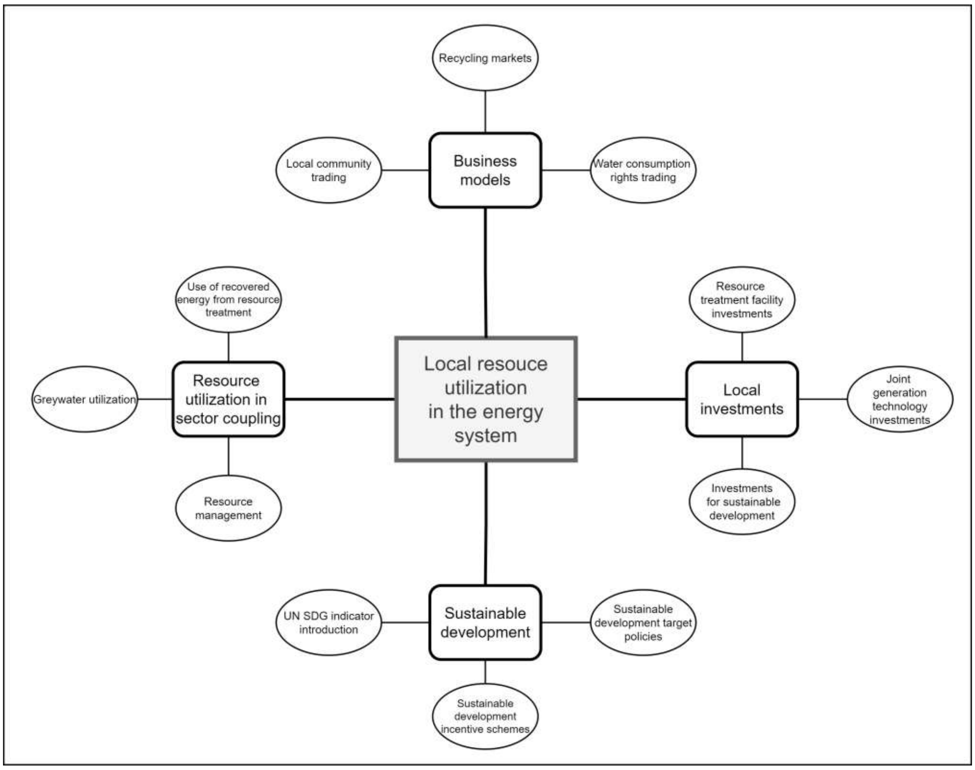

Figure 7.1.: Opportunities for local resource utilization in the energy system

requires grid infrastructure to exploit its full potential. The infrastructure requirement can make the concept only applicable in areas with sufficient infrastructure. Moreover, the space provision of treatment plants might emerge as a barrier in certain regions, limiting the transferability of the introduced energy recovery concepts to areas with sufficient space and grid connection. Furthermore, installing treatment plants in exposed areas could lead to difficulties and inefficiencies, as the transport distance of resources might be too high. However, energy recovery from resource treatment leads to higher process efficiency and a circular economy. Therefore, implementing energy recovery potential leads to additional advantages and should be used wherever possible. The findings of the research are thus transferable but strongly depend on the system configuration, but also on available technologies

Knickmeyer (2020) stated that waste management is a global issue, requiring locally adapted strategies. Moreover, water utilization gains opportunities in local reuse (Angelakis et al., 2018). Thus, the scaling of resource utilization concepts in sector coupling is connected with challenges, as the scale of implementation can be vital. The approaches in this thesis considered downscaling of resource treatment processes rather than upscaling. Scaling of local waste treatment facilities is limited, as providing multiple local treatment plants might not be economically efficient. However, the results in this paper showed high potential if such treatment plants could be locally utilized in the future. Benefits could emerge if multiple communities or municipalities jointly invest in local treatment facilities. Sewage treatment plants are often locally implemented. However, exploiting energy recovery from sludge treatment requires similar decentralization approaches to waste treatment and therefore may result in similar scaling difficulties. Therefore, upscaling of all findings is not directly applicable, as the utilization of resources strongly depends on the considered scale.

Business models are vital to encourage consumers to utilize efficient local operations and resources. Therefore, it is crucial to reduce the waste of services in such communities (Haas et al., 2008). Local business models can be widely implemented by community concepts such as ECs. However, the legal frameworks for ECs differ between European countries, leading to difficulties in transferability (Maldet et al., 2022a). The introduced business models for resource utilization consider energy recovery and resource reduction. The transferability of energy recovery business models requires the availability of such services. Moreover, treatment plant operators must agree to provide such business models to communities. Furthermore, implementing energy recovery business models requires grid connection, which can lead to barriers as not all consumers are connected to district heating grids. Thus, heat recovery business models are only applicable to communities with district heat connections. Waste and water reduction business models require less supportive technologies and infrastructure. The mainly required devices for the rollout of such business models in multiple communities are smart meters for water and waste amount scales. The significant limiting factor for the transferability of reduction business models might be the mandatory community participants' agreements for taking part in such reduction programs. Consumers not willing to reduce their water demand could reject reduction contracts. The problem of the lack of participation in waste recycling markets could be overcome by setting sufficiently high waste market prices, which could encourage community participants to increase recycling to generate revenues.

The upscaling of business models depends on various aspects. Critical factors for the implementation of a circular economy include stakeholder involvement, social relationships and appropriate technology finding (Aguiñaga et al., 2018). The upscaling might limit the applicability of some of the introduced business models. The results showed that a transition from local communities to business models in municipalities leads to different community operations. Trading was performed less in communities with a larger scale of implementation. Moreover, resource utilization mainly focuses on investments in treatment facilities and the exploitation of recovered energy. Thus, reduction business models might not be applicable to communities with a higher scale of implementation. However, even though local community business models might not be scalable, community scales at higher levels could lead to the applicability of diverse business models. Thus, particular designed local resource utilization business models are hardly scalable, but they can be adapted to the scope of community implementation.

Similar to general resource utilization concepts, local capacity investment depends on the configuration of the considered system. Therefore, the impact of assets differs in various setups, making the findings on resource utilizations transferable with limitations. Investment decisions depend on multiple parameters, including interest rate, costs for power supply and governmental subsidies (Silveira et al., 2013). Additionally, the capacity investment depends on current market prices (Fleten et al., 2007). The economic feasibility of technology investment depends on the implemented business models and thus on opportunities for technology utilization. Implemented energy recovery can promote investments in infrastructure, such as district heat connection. However, this is only valid for regions where recovered heat can be utilized from resource treatment processes. Moreover, strategies of local authorities in the considered area can affect investments. Policy goals such as self-sufficiency or local energy and resource utilization directly impact investment strategies. Various policies might lead to different investments than those implicated by market aspects. Furthermore, sustainable development targets in specific configurations affect investments. The same counts for sustainable development incentive schemes. Thus, findings on investments are transferable, but they strongly depend on local configurations and strategies.

The scale of the considered configuration strongly affects the investments. A larger scale increases capacity investments due to higher technology potential and economies of scale effects. This thesis mainly focuses on local technology investments, showing potential in local investments for resource treatment and energy recovery. Investments in sustainable technology are not guaranteed to positively affect the environment (Wang et al., 2021). However, in the analyses of this thesis, investments in resource treatment facilities and the corresponding implementation of energy recovery lead to benefits for the considered system, independent of the scale. Therefore, the findings of this thesis regarding local resource treatment investments are applicable at different scales.

The introduction of sustainability indicators can promote sustainable development. Challenges for such indicators arise in potential conflicts between them (Afshari et al., 2022). Thus, the adoption of multi-criteria approaches should be considered for indicator development (Klemm and Wiese, 2022). The goal of the UN SDG indicator establishment was the development of nationally relevant indicators. However, these indicators are similarly applicable in other developed countries than Austria. Particularities of certain countries could be further considered in potential adaptations in other nations, leading to a higher level of transferability. Thus, the establishment of the proposed UN SDG indicator is transferable. The impact of indicator application differs depending on community and municipality configuration. Adaptations or exemptions could be implemented in certain configurations to reach particular targets. However, this does not affect the applicability and positive impact of the introduction of the UN SDG indicator on sustainable community and municipality development. The findings for local sustainable development with indicator introduction are thus transferable to other communities and municipalities.

The developed UN SDG indicators are tailored for local communities and municipalities. According to Gunnarsdottir et al. (2022), sustainability indicators often reflect critical issues. Thus, the indicators consider potentially available services and technologies. An upscaling requires the inclusion of additional technologies, thus leading to higher indicator complexity. However, an adaptation and thus an upscaling are possible if additional service and technology impact can be evaluated.

In summary, the introduced concepts for resource utilization in sector coupling, including business models, investments, and UN SDG indicators, are transferable. Potential adaptions to local environmental conditions and configurations might be necessary for the implementation of such concepts at particular sites. Moreover, adaptions could be required for different scales of performance. However, without unique particularities in certain configurations, the findings of this thesis are transferable and can be applied to different implementation scales.

7.3. Strengths and limitations

This section addresses the strengths and limitations of this thesis' proposed methods and approaches. Section 7.3.1 addresses the strengths of the proposed methods. Section 7.3.2 focuses on potential hurdles in the modeling approaches and concepts for resource utilization in sector coupling.

7.3.1. Strengths in the proposed methods

This section presents the strengths of the proposed methods, in particular from the modeling framework and resource utilization perspective.

The developed RUTIS modeling framework is established as a modular optimization framework. It implements basic functionalities of the OEMOF framework (Hilpert et al., 2018), with the modular implementation of components and functionalities. The framework considers multiple energy sectors and resource utilization. Energy systems can be simulated by building the systems out of RUTIS components, making the framework adaptable and versatile. Multiple analyses can be performed for the same systems by adding or removing energy system components of the framework or by changing parameters. Moreover, the framework implements basic technology parameters with possible alterations for particular analyses. The framework can be extended by adding additional components or functionalities without affecting existing functionalities. Additional functionalities of the RUTIS framework include the consideration and interactions between multiple consumers. Thus, the framework is applicable for multiple consumer sector coupling investigations and EC business models can be applied and simulated with the framework. Further extensions of the framework consider investment decisions. Like other functionalities, investment decisions can be performed by adding the corresponding components to the energy system, with possible alterations of investment costs and maximum capacities. Therefore, the modular approach provides advantages for the implementation of investment decisions.

Further strengths of the method include the modeling approach. Sector coupling investigations include the implementation of resources, whereas the model considers resources as additional inputs or outputs of conversion technologies. The relationships are defined by conversion factors, leading to multiple input-output interactions by energy system components. Therefore, the introduced concepts can address the complexity of resource utilization in sector coupling.

Furthermore, the consideration of multiple consumers allows the application of business models and the investigation of the impact on consumers. Business models for local communities can be extended to waste and water by additional modeling of resource utilization. The analyzed business models include energy recovery, greywater utilization and resource management. Thus, the strength of the approach is the versatile implementation of such business models and their direct comparability regarding the impact on the energy system. Moreover, the impact of business models on operational efficiency can be directly assessed. A further strength of the method emerges in the localization of resource treatment facilities. The approach provides a simplified method for determining the location of such facilities within municipalities and provides implications for treatment site determinations.

Furthermore, the strengths of the analyses include the consideration of different local market scopes. The research considers various implementations of local markets and addresses the impact of operations. Thus, the study can give implications for local market implementation, depending on the considered scope. The newly introduced concepts of LSCs and LSMs can provide applicable long-term concepts with a clear definition and implementation. These concepts can be widely established in communities and municipalities and provide benefits to their participants. Moreover, these community concepts can extend traditional ECs by resource utilization and provide opportunities for local sustainable development.

Finally, a crucial strength of the approach is the consideration of the UN SDG. The method applies indicators and policy actions to achieve particular SDG targets. Thus, this research gives implications on actions and policies for local sustainable development.

7.3.2. Limitations in the modeling approaches

This section focuses on the limitations regarding model implementation and modeling approaches. The developed model considers functionalities for resource utilization in sector coupling. However, due to the complexity, the particular implementation of the sectors and technologies is limited. The generation and conversion technologies are kept simple for implementation, whereas generation technologies are implemented with generation time series. Technological parameters for conversion technologies are implemented with conversion factors and input and output limits. However, multiple inputs and outputs of the technologies are possible. Besides the model implementation, technology operations are considered as black boxes, lacking the detailed implementation of technology operation and impact assessment. Therefore, the method limits the analyses to technology interaction analyses. Thus, future studies considering resource utilization in sector coupling could focus on a particular impact on technologies in sector coupling.

Furthermore, not all analyses consider technology investments. Studies that consider technology investments provide simplifications due to the high level of complexity in sector coupling with multiple consumer investment decisions. Thus, the investment decisions in the model focus on particular research questions. Simplifications were performed to keep the model size at an acceptable level. Therefore, future research could apply sophisticated investment decision methods in sector-coupled energy systems with resource utilization. Moreover, grid infrastructure is assumed to be sufficiently installed in all analyses. However, deploying energy recovery infrastructure could cause loads on the electricity and district heat grids, leading to potential grid extension requirements. Therefore, extensions of the introduced concepts for energy recovery should consider impact assessments on the grids at the sites.

Waste is implemented in the form of MSW, being considered as a black box in the approaches. However, different kinds of waste result in different environmental impacts and treatment challenges. The moisture of biowaste can affect energy recovery (Zhao et al., 2014). Moreover, treatment options can vary between different kinds of MSW. Another area for improvement is the neglect of waste separation process modelling at treatment sites. Investigations in this work assume that waste is perfectly separated, and the separation requires no costs, energy or effort. Future research could focus on more detailed modeling of the waste sector with different kinds of MSW and detailed models of the waste supply chain. Similar to waste, water and sewage are mainly considered as black boxes in the model. The model does not consider energy utilization for water distribution to consumers. Moreover, the model does not include water quality as a parameter, limiting the water investigations to potable water, sewage and greywater As for waste treatment, preliminary processes for sludge treatment are not considered in the approach. Therefore, future research could focus on more detailed modeling of the water sector by considering all water supply and sewage treatment processes. Furthermore, the modelling approaches consider waste and water implementation in traditional energy sectors. However, the hydrogen sector emerges as an additional sector, providing new opportunities for the energy system. Due to the already high level of complexity, the hydrogen sector was not implemented in the analyses. Future technological model extensions could thus consider sectoral waste and water interaction with hydrogen.

Further limitations of the approaches arise in the community analyses. The model implements particular consumer operations. However, direct interactions between consumers were not modelled but were rather performed over community interfaces. Thus, detailed analyses of local Peer-to-peer (P2P) trading were not implemented, leading to potential limitations for detailed consumer impact assessments. Model extensions could replace community interfaces with single P2P interaction modeling. Similar assessment limitations emerge in the determination of energy flows. Many analyses for the communities consider the trading of energy, but also resource rights in communities. Those trades are implemented as virtual energy and resource flows. Due to missing detailed grid infrastructure modeling and consumer localization in some of the analyses, the model does not consider the impact on real energy flows within grids. Future work could address the effects on energy and resource flows by performing a second modeling step considering physical flows.

Finally, limitations arise in the considered scope of community operations. Community analyses are limited through defined system boundaries. Consumers can interact within a community but are limited in their operations beyond the community boundaries. Such interactions are not directly addressed by the modeling approaches. Therefore, future work could focus on multi-community interactions. The same counts for interactions between multiple municipalities within a region. Future work could model multiple municipality interactions, and consider joint resource treatment facilities for multiple municipalities and analyze the impact of such.

8. Conclusions and outlook

Resource utilization in sector coupling on the local level can result in cost and environmental benefits to consumers and energy system operations. This thesis provides new insights by including waste and water resources in local sector coupling analyses. This section concludes the findings in this thesis and presents an outlook on potential future developments in the topic.

The applied method in the analyses included the development of an optimization framework for multiple-consumer sector coupling. This framework proved to be applicable for the elaboration of the research questions. The modular implementation of the framework provided flexibility for different investigations, leading to extension possibilities for addressing particular issues. By considering several energy and service sectors, in combination with multiple consumer modeling, the framework provided the required functionalities for analyzing local resource utilization in sector coupling and the application of business models. However, the inclusion of waste and water in sector coupling modeling increases complexity, limiting the detailed sectoral implementations of technologies and interactions. This complexity could be decreased by implementing community managers as a central interface for trading and joint technology implementation. Investment decision consideration could provide further opportunities for the proposed methods. However, considering investment decisions for multiple sectors and consumers led to large model sizes. The proposed modeling framework which included clustering of the input data led to significant model size reductions but limited the approach to capacity localization and estimation.

The results indicated a high potential for local resource utilization in sector coupling. Waste and water implementation in energy system analyses can provide significant contributions to the energy system using recovered energy from resource treatment processes. However, exploiting the full potential of energy recovery requires resource management and treatment planning. Opportunities for local resource utilization emerge through community establishment. Joint implementation of resource-related processes in local energy systems could be promoted by the community spirit. The local market implementation depends on the scope of the communities. Community establishment enables the implementation of energy and resource-related business models. The business models resulted in cost reduction for consumers and in the more efficient local operation of technologies. Moreover, the introduction of water consumption rights trading led to higher water efficiency and could address water scarcity. However, the implementation requires contracts between multiple community participants that agree on water demand reductions and higher costs for non-reached targets. Such contracts could emerge as a barrier and prevent the implementation of water consumption rights trading. Waste recycling could be promoted by implementing a local recycling market for secondary materials. However, these compete with waste treatment energy recovery business models. Efficiently high recycling market prices are thus required to encourage consumers to participate in such markets.

Investments in clean technologies in combination with local resource treatment facilities with the utilization of energy recovery could further promote system efficiency. Greywater system installation can decrease the load on local sewage treatment plants and address the increasing issues of water scarcity in various regions. However, greywater installation requires high costs for investments and thus, the advantages should be considered from an environmental perspective rather than a financial perspective. Moreover, sufficient decentralization could be hindered in implementation due to the high costs of waste treatment facilities. Therefore, future developments in waste treatment should consider additional options for local waste treatment investments to exploit the full potential of energy recovery and to lower the distances in the disposal chain. Such investments were further affected by local decisions, where particular strategies always lead to overinvestment and thus to higher costs. It must therefore be weighed up whether the costs of achieving the objectives are justified.

Business models and investments for local resource utilization in sector coupling could promote sustainable development according to the UN SDG. This could be further encouraged by the introduction of indicators for local UN SDG contributions. However, most indicators in the literature consider various and complex indicators for the SDGs. Therefore, this thesis introduced simple and applicable indicators. The proposed indicators led to additional contributions to local sustainable development by promoting investment in otherwise not implemented technologies. However, the application should be performed regarding particular SDG targets and policies.

Due to the wide range of opportunities, this thesis could only address particular aspects of local resource utilization in sector coupling. The provided methodological approaches and the introduced modeling framework can be extended to exploit new research on the topic. Future research could include detailed technology modeling in sector coupling approaches. Furthermore, future research should consider detailed modeling of the waste sector, considering different shares of waste by addressing particularities of such. The analyses could further be extended to additional sectors such as the hydrogen sector. Furthermore, future work could extend or apply new local resource utilization business models, that can further promote efficient local resource utilization. Potential future research could also include community extensions, addressing joint treatment facility operations and investments over multiple municipalities.

9. References

Books

Brauner, Günther (2022). *Efficiency Through Sector Coupling*. Ed. by Günther Brauner. Springer Fachmedien Wiesbaden, pp. 209–224. ISBN: 978-3-658-35138-0. DOI: 10.1007/978-3-658-35138-0_10. URL: https://doi.org/10.1007/978-3-658-35138-0_10 (cit. on p. 17).

Egan, John (2004). *The Egan Review: Skills for Sustainable Communities*. RIBA Enterprises (cit. on pp. 4, 47).

ISO (July 2018). *ISO 37120:2018: Sustainable cities and communities — Indicators for city services and quality of life*. ISO, p. 121. URL: https://www.iso.org/standard/68498.html (cit. on pp. 26, 123).

Norbury, James (2020). *Big Panda and Tiny Dragon*. Michael Joseph, p. 12 (cit. on p. I).

Vu, Minh T, Luong N Nguyen, Jakub Zdarta, Johir A H Mohammed, Nirenkumar Pathak, and Long D Nghiem (2022). *Chapter 1 - Wastewater to R3 – resource recovery, recycling, and reuse efficiency in urban wastewater treatment plants*. Ed. by Alicia An, Vinay Tyagi, Manish Kumar, and Zeynep Cetecioglu. Elsevier, pp. 3–16. ISBN: 978-0-323-90178-9. DOI: https://doi.org/10.1016/B978-0-323-90178-9.00014-7. URL: https://www.sciencedirect.com/science/article/pii/B9780323901789000147 (cit. on p. 15).

Journal Articles

Afshari, H., S. Agnihotri, C. Searcy, and M. Y. Jaber (May 2022). "Social sustainability indicators: A comprehensive review with application in the energy sector”. In: *Sustainable Production and Consumption* 31, pp. 263–286. ISSN: 2352-5509. DOI: 10.1016/J.SPC.2022.02.018. URL: https://www.sciencedirect.com/science/article/abs/pii/S2352550922000501 (cit. on p. 167).

Aguiñaga, Eduardo, Irene Henriques, Carlos Scheel, and Andrea Scheel (Feb. 2018). “Building resilience: A self-sustainable community approach to the triple bottom line”. In: *Journal of Cleaner Production* 173, pp. 186–196. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2017.01.094. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652617301087 (cit. on p. 166).

Ahmad, Jamil and Hisham EL-Dessouky (May 2008). “Design of a modified low cost treatment system for the recycling and reuse of laundry waste water”. In: *Resources, Conservation and Recycling* 52 (7), pp. 973–978. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2008.03.001. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344908000359?via%3Dihub (cit. on p. 16).

Aivazidou, Eirini (2022). “Water Management in Agriculture and Industry: Challenges, Trends, and Opportunities”. In: *Sustainability* 14 (1). ISSN: 2071-1050. DOI: 10.3390/su14010066. URL: https://www.mdpi.com/2071-1050/14/1/66 (cit. on pp. 15, 20).

Akinyele, D. O., N. K. C. Nair, R. K. Rayudu, and B. Chakrabarti (2014). “Decentralized energy generation for end-use applications: Economic, social and environmental benefits assessment”. In: *2014 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)*, pp. 84–89. DOI: 10.1109/ISGT-Asia.2014.6873769. URL: https://ieeexplore.ieee.org/document/6873769 (cit. on p. 3).

Alam, Ohidul and Xiuchen Qiao (Jan. 2020). “An in-depth review on municipal solid waste management, treatment and disposal in Bangladesh”. In: *Sustainable Cities and Society* 52, p. 101775. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2019.101775. URL: https://www.sciencedirect.com/science/article/pii/S2210670719307061 (cit. on p. 22).

Alstone, Peter, Dimitry Gershenson, and Daniel M Kammen (2015). “Decentralized energy systems for clean electricity access”. In: *Nature Climate Change* 5 (4), pp. 305–314. ISSN: 1758-6798. DOI: 10.1038/nclimate2512. URL: https://doi.org/10.1038/nclimate2512 (cit. on p. 21).

Alzamora, Bruno Ribas and Raphael Tobias de V. Barros (2020). "Review of municipal waste management charging methods in different countries". In: *Waste Management* 115, pp. 47–55. ISSN: 0956-053X. DOI: https://doi.org/10.1016/j.wasman.2020.07.020. URL: https://www.sciencedirect.com/science/article/pii/S0956053X2030386X (cit. on p. 22).

Ameen, Raed Fawzi Mohammed and Monjur Mourshed (Jan. 2019). "Urban sustainability assessment framework development: The ranking and weighting of sustainability indicators using analytic hierarchy process". In: *Sustainable Cities and Society* 44, pp. 356–366. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2018.10.020. URL: https://www.sciencedirect.com/science/article/abs/pii/S221067071830266X (cit. on p. 23).

Amulen, Judith, Hillary Kasedde, Jonathan Serugunda, and Joseph D. Lwanyaga (May 2022). "The potential of energy recovery from municipal solid waste in Kampala City, Uganda by incineration". In: *Energy Conversion and Management: X* 14, p. 100204. ISSN: 2590-1745. DOI: 10.1016/J.ECMX.2022.100204. URL: https://www.sciencedirect.com/science/article/pii/S2590174522000277?via%3Dihub (cit. on p. 15).

Anastaselos, Dimitrios, Simeon Oxizidis, Alexandros Manoudis, and Agis M. Papadopoulos (Jan. 2016). "Environmental performance of energy systems of residential buildings: Toward sustainable communities". In: *Sustainable Cities and Society* 20, pp. 96–108. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2015.10.006. URL: https://www.sciencedirect.com/science/article/pii/S2210670715300457 (cit. on p. 20).

Angelakis, Andreas N, Takashi Asano, Akissa Bahri, Blanca E Jimenez, and George Tchobanoglous (2018). "Water Reuse: From Ancient to Modern Times and the Future". In: *Frontiers in Environmental Science* 6. ISSN: 2296-665X. DOI: 10.3389/fenvs.2018.00026. URL: https://www.frontiersin.org/articles/10.3389/fenvs.2018.00026 (cit. on p. 165).

Anuja, J, B Darshan, G Saraswathi, and N Meyyappan (2021). "Study on reuse of grey water – A Review". In: *Journal of Physics: Conference Series* 1979 (1), p. 012004. ISSN: 1742-6588. DOI: 10.1088/1742-6596/1979/1/012004. URL: http://dx.doi.org/10.1088/1742-6596/1979/1/012004 (cit. on p. 16).

Arnaudo, Monica, Johan Dalgren, Monika Topel, and Björn Laumert (Mar. 2021). “Waste heat recovery in low temperature networks versus domestic heat pumps - A techno-economic and environmental analysis”. In: *Energy* 219, p. 119675. ISSN: 0360-5442. DOI: 10.1016/J.ENERGY.2020.119675. URL: https://www.sciencedirect.com/science/article/pii/S0360544220327821?via%3Dihub (cit. on p. 17).

Ayoub, Mohamed, Ibrahim Rashed, and Ahmed El-Morsy (May 2016). “Energy Production from Sewage Sludge in a Proposed Wastewater Treatment Plant”. In: *Civil Engineering Journal* 2, pp. 637–645. DOI: 10.28991/cej-2016-00000064. URL: https://civilejournal.org/index.php/cej/article/view/223 (cit. on p. 227).

Babalola, Samuel O., Joshua J. Nel, Victor Tshigo, Michael O. Daramola, and Samuel A. Iwarere (Apr. 2022). “An integrated waste-to-energy approach: A resilient energy system design for sustainable communities”. In: *Energy Conversion and Management* 258, p. 115551. ISSN: 0196-8904. DOI: 10.1016/J.ENCONMAN.2022.115551. URL: https://www.sciencedirect.com/science/article/abs/pii/S0196890422003478?via%3Dihub (cit. on p. 20).

Bain, Robert, Richard Johnston, Francesco Mitis, Christie Chatterley, and Tom Slaymaker (2018). “Establishing Sustainable Development Goal Baselines for Household Drinking Water, Sanitation and Hygiene Services”. In: *Water* 10 (12). ISSN: 2073-4441. DOI: 10.3390/w10121711. URL: https://www.mdpi.com/2073-4441/10/12/1711 (cit. on p. 25).

Battista, Davide Di, Chiara Barchiesi, Luca Di Paolo, Simona Abbate, Sara Sorvillo, Andrea Cinocca, Roberto Carapellucci, Dario Ciamponi, Dina Cardone, Salvatore Corroppolo, and Roberto Cipollone (2021). “The Reporting of Sustainable Energy Action Plans of Municipalities: Methodology and Results of Case Studies from the Abruzzo Region”. In: *Energies* 14 (18). ISSN: 1996-1073. DOI: 10.3390/en14185932. URL: https://www.mdpi.com/1996-1073/14/18/5932 (cit. on p. 19).

Bernath, Christiane, Gerda Deac, and Frank Sensfuß (Jan. 2021). “Impact of sector coupling on the market value of renewable energies – A model-based scenario analysis”. In: *Applied Energy* 281, p. 115985. ISSN: 0306-2619. DOI: 10.1016/J.APENERGY.2020.115985. URL: https://www.sciencedirect.com/science/article/abs/pii/S0306261920314331?via%3Dihub (cit. on p. 163).

Bertanza, G., E. Ziliani, and L. Menoni (Apr. 2018). "Techno-economic performance indicators of municipal solid waste collection strategies". In: *Waste Management* 74, pp. 86–97. ISSN: 0956-053X. DOI: 10.1016/J.WASMAN.2018.01.009. URL: https://www.sciencedirect.com/science/article/abs/pii/S0956053X18300096 (cit. on p. 23).

Bertoldi, Paolo and Rocco Mosconi (Apr. 2020). "Do energy efficiency policies save energy? A new approach based on energy policy indicators (in the EU Member States)". In: *Energy Policy* 139, p. 111320. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2020.111320. URL: https://www.sciencedirect.com/science/article/pii/S030142152030077X (cit. on p. 23).

Bezerra, Maíra Ometto et al. (2022). "Operationalizing Integrated Water Resource Management in Latin America: Insights from Application of the Freshwater Health Index". In: *Environmental Management* 69 (4), pp. 815–834. ISSN: 1432-1009. DOI: 10.1007/s00267-021-01446-1. URL: https://doi.org/10.1007/s00267-021-01446-1 (cit. on p. 24).

Bibri, Simon Elias (Apr. 2018). "A foundational framework for smart sustainable city development: Theoretical, disciplinary, and discursive dimensions and their synergies". In: *Sustainable Cities and Society* 38, pp. 758–794. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2017.12.032. URL: https://www.sciencedirect.com/science/article/pii/S2210670717313069 (cit. on p. 19).

Bortoluzzi, Mirian, Celso Correia de Souza, and Marcelo Furlan (June 2021). "Bibliometric analysis of renewable energy types using key performance indicators and multicriteria decision models". In: *Renewable and Sustainable Energy Reviews* 143, p. 110958. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2021.110958. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032121002501 (cit. on p. 23).

Brandoni, Caterina and Fabio Polonara (Dec. 2012). "The role of municipal energy planning in the regional energy-planning process". In: *Energy* 48 (1), pp. 323–338. ISSN: 0360-5442. DOI: 10.1016/J.ENERGY.2012.06.061. URL: https://www.sciencedirect.com/science/article/abs/pii/S0360544212005130 (cit. on p. 20).

Braulio-Gonzalo, Marta, María Dolores Bovea, and María José Ruá (July 2015). "Sustainability on the urban scale: Proposal of a structure of indicators for the Spanish context". In: *Environmental Impact Assessment Review* 53, pp. 16–30. ISSN: 0195-9255. DOI: 10.1016/J.EIAR.2015.03.

002. URL: https://www.sciencedirect.com/science/article/abs/pii/S0195925515000311 (cit. on p. 24).

Campos, J L, D Valenzuela-Heredia, A Pedrouso, A Val del Río, M Belmonte, and A Mosquera-Corral (2016). "Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention". In: *Journal of Chemistry* 2016. Ed. by Claudio Di Iaconi, p. 3796352. ISSN: 2090-9063. DOI: 10.1155/2016/3796352. URL: https://www.hindawi.com/journals/jchem/2016/3796352/ (cit. on pp. 229, 236, 257).

Capodaglio, A G, A Callegari, D Cecconet, and D Molognoni (June 2017). "Sustainability of decentralized wastewater treatment technologies". In: *Water Practice and Technology* 12 (2), pp. 463–477. ISSN: 1751-231X. DOI: 10.2166/wpt.2017.055. URL: https://doi.org/10.2166/wpt.2017.055 (cit. on p. 22).

Cecconet, Daniele, Jakub Raček, Arianna Callegari, and Petr Hlavínek (2020). "Energy Recovery from Wastewater: A Study on Heating and Cooling of a Multipurpose Building with Sewage-Reclaimed Heat Energy". In: *Sustainability* 12 (1). ISSN: 2071-1050. DOI: 10.3390/su12010116. URL: https://www.mdpi.com/2071-1050/12/1/116 (cit. on p. 227).

Chen, Chong Wen (Mar. 2021). "Clarifying rebound effects of the circular economy in the context of sustainable cities". In: *Sustainable Cities and Society* 66, p. 102622. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2020.102622. URL: https://www.sciencedirect.com/science/article/pii/S2210670720308398 (cit. on p. 22).

Chen, Ying Chu (Aug. 2018). "Evaluating greenhouse gas emissions and energy recovery from municipal and industrial solid waste using waste-to-energy technology". In: *Journal of Cleaner Production* 192, pp. 262–269. ISSN: 09596526. DOI: 10.1016/j.jclepro.2018.04.260. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652618313027?via%3Dihub (cit. on p. 14).

Chen, Ying Chu and Jeff Kuo (Aug. 2016). "Potential of greenhouse gas emissions from sewage sludge management: a case study of Taiwan". In: *Journal of Cleaner Production* 129, pp. 196–201. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2016.04.084. URL: https://www.sciencedire ct.com/science/article/abs/pii/S0959652616303602?via%3Dihub (cit. on p. 229).

Christova-Boal, Diana, Robert E. Eden, and Scott McFarlane (Aug. 1996). "An investigation into greywater reuse for urban residential properties". In: *Desalination* 106 (1-3), pp. 391–397. ISSN: 0011-9164. DOI: 10.1016/S0011-9164(96)00134-8. URL: https://www.sciencedirect.com/science/article/abs/pii/S0011916496001348?via%3Dihub (cit. on pp. 16, 94).

Chung, William (May 2011). "Review of building energy-use performance benchmarking methodologies". In: *Applied Energy* 88 (5), pp. 1470–1479. ISSN: 0306-2619. DOI: 10.1016/J.APENERGY.2010.11.022. URL: https://www.sciencedirect.com/science/article/abs/pii/S030626191000485X (cit. on pp. 4, 24).

Cialani, Catia and Reza Mortazavi (Apr. 2020). "The Cost of Urban Waste Management: An Empirical Analysis of Recycling Patterns in Italy". In: *Frontiers in Sustainable Cities* 2, pp. 1–9. DOI: 10.3389/frsc.2020.00008. URL: https://www.frontiersin.org/articles/10.3389/frsc.2020.00008/full (cit. on p. 93).

Cielo, A., P. Margiaria, P. Lazzeroni, I. Mariuzzo, and M. Repetto (Sept. 2021). "Renewable Energy Communities business models under the 2020 Italian regulation". In: *Journal of Cleaner Production* 316, p. 128217. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2021.128217. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652621024343?via%3Dihub (cit. on p. 19).

Corsten, Mariëlle, Ernst Worrell, Magda Rouw, and Armande Van Duin (Aug. 2013). "The potential contribution of sustainable waste management to energy use and greenhouse gas emission reduction in the Netherlands". In: *Resources, Conservation and Recycling* 77, pp. 13–21. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2013.04.002. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344913000888?via%3Dihub (cit. on p. 15).

Couto, Eduardo De Aguiar Do, Maria Lúcia Calijuri, Paula Peixoto Assemany, Aníbal Da Fonseca Santiago, and Isabella De Castro Carvalho (Aug. 2013). "Greywater production in airports: Qualitative and quantitative assessment". In: *Resources, Conservation and Recycling* 77, pp. 44–51. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2013.05.004. URL:

https://www.sciencedirect.com/science/article/abs/pii/S0921344913001134?via%3Dihub (cit. on p. 16).

Cureau, Roberta Jacoby and Enedir Ghisi (2019). "Reduction of Potable Water Consumption and Sewage Generation on a City Scale: A Case Study in Brazil". In: *Water* 11 (11). ISSN: 2073-4441. DOI: 10.3390/w11112351. URL: https://www.mdpi.com/2073-4441/11/11/2351 (cit. on pp. 17, 22).

Damari, Yuval and Meidad Kissinger (Aug. 2018). "An integrated analysis of households' electricity consumption in Israel". In: *Energy Policy* 119, pp. 51–58. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2018.04.010. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421518302234?via%3Dihub (cit. on p. 225).

Demirbas, Ayhan (Feb. 2011). "Waste management, waste resource facilities and waste conversion processes". In: *Energy Conversion and Management* 52 (2), pp. 1280–1287. ISSN: 0196-8904. DOI: 10.1016/J.ENCONMAN.2010.09.025. URL: https://www.sciencedirect.com/science/article/abs/pii/S0196890410004279?via%3Dihub (cit. on p. 3).

Di Vaio, Assunta, Sohail Hasan, Rosa Palladino, and Rohail Hassan (Jan. 2023). "The transition towards circular economy and waste within accounting and accountability models: a systematic literature review and conceptual framework". In: *Environment, Development and Sustainability* 25.1, pp. 734–810. ISSN: 1573-2975. DOI: 10.1007/s10668-021-02078-5. URL: https://doi.org/10.1007/s10668-021-02078-5 (cit. on p. 13).

Ding, An, Rourou Zhang, Huu Hao Ngo, Xu He, Jun Ma, Jun Nan, and Guibai Li (May 2021). "Life cycle assessment of sewage sludge treatment and disposal based on nutrient and energy recovery: A review". In: *Science of The Total Environment* 769, p. 144451. ISSN: 0048-9697. DOI: 10.1016/J.SCITOTENV.2020.144451. URL: https://www.sciencedirect.com/science/article/abs/pii/S0048969720379821?via%3Dihub (cit. on p. 20).

Ding, Yong and Xue Liu (Feb. 2020). "A comparative analysis of data-driven methods in building energy benchmarking". In: *Energy and Buildings* 209, p. 109711. ISSN: 0378-7788. DOI: 10.1016/J.ENBUILD.2019.109711. URL: https://www.sciencedirect.com/science/article/abs/pii/S037877881932047X (cit. on p. 24).

Dlamini, Smangele, Mulala Danny Simatele, and Nzalalemba Serge Kubanza (Mar. 2019). "Municipal solid waste management in South Africa: from waste to energy recovery through waste-to-energy technologies in Johannesburg". In: *Local Environment* 24 (3), pp. 249–257. ISSN: 1354-9839. DOI: 10.1080/13549839.2018.1561656. URL: https://doi.org/10.1080/13549839.2018.1561656 (cit. on pp. 3, 14, 17).

Drago, Carlo and Andrea Gatto (Aug. 2022). "Policy, regulation effectiveness, and sustainability in the energy sector: A worldwide interval-based composite indicator". In: *Energy Policy* 167, p. 112889. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2022.112889. URL: https://www.sciencedirect.com/science/article/pii/S0301421522001148 (cit. on p. 23).

Dubey, Rameshwar, Angappa Gunasekaran, Stephen J. Childe, Thanos Papadopoulos, Benjamin Hazen, Mihalis Giannakis, and David Roubaud (Nov. 2017). "Examining the effect of external pressures and organizational culture on shaping performance measurement systems (PMS) for sustainability benchmarking: Some empirical findings". In: *International Journal of Production Economics* 193, pp. 63–76. ISSN: 0925-5273. DOI: 10.1016/J.IJPE.2017.06.029. URL: https://www.sciencedirect.com/science/article/abs/pii/S0925527317302025 (cit. on p. 24).

Edtmayer, Hermann, Peter Nageler, Richard Heimrath, Thomas Mach, and Christoph Hochenauer (Sept. 2021). "Investigation on sector coupling potentials of a 5th generation district heating and cooling network". In: *Energy* 230, p. 120836. ISSN: 0360-5442. DOI: 10.1016/J.ENERGY.2021.120836. URL: https://www.sciencedirect.com/science/article/pii/S0360544221010847?via%3Dihub (cit. on p. 17).

Evans, Annette, Vladimir Strezov, and Tim J. Evans (June 2009). "Assessment of sustainability indicators for renewable energy technologies". In: *Renewable and Sustainable Energy Reviews* 13 (5), pp. 1082–1088. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2008.03.008. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032108000555 (cit. on p. 23).

Fleten, S. E., K. M. Maribu, and I. Wangensteen (May 2007). "Optimal investment strategies in decentralized renewable power generation under uncertainty". In: *Energy* 32 (5), pp. 803–815. ISSN: 0360-5442. DOI: 10.1016/J.ENERGY.2006.04.015. URL: https://www.sciencedirect.

com/science/article/abs/pii/S0360544206001150?via%3Dihub (cit. on p. 166).

Franzoi, Nicola, Alessandro Prada, Sara Verones, and Paolo Baggio (2021). "Enhancing PV Self-Consumption through Energy Communities in Heating-Dominated Climates". In: *Energies* 14 (14). ISSN: 1996-1073. DOI: 10.3390/en14144165. URL: https://www.mdpi.com/1996-1073/14/14/4165 (cit. on p. 19).

Fridgen, Gilbert, Robert Keller, Marc Fabian Körner, and Michael Schöpf (Dec. 2020). "A holistic view on sector coupling". In: *Energy Policy* 147, p. 111913. ISSN: 03014215. DOI: 10.1016/j.enpol.2020.111913. URL: https://www.sciencedirect.com/science/article/pii/S0301421520306248?via%3Dihub (cit. on p. 17).

Gea-Bermúdez, Juan, Ida Græsted Jensen, Marie Münster, Matti Koivisto, Jon Gustav Kirkerud, Yi kuang Chen, and Hans Ravn (May 2021). "The role of sector coupling in the green transition: A least-cost energy system development in Northern-central Europe towards 2050". In: *Applied Energy* 289, p. 116685. ISSN: 03062619. DOI: 10.1016/j.apenergy.2021.116685. URL: https://www.sciencedirect.com/science/article/abs/pii/S0306261921002130?via%3Dihub (cit. on pp. 3, 17).

Geissdoerfer, Martin, Sandra Naomi Morioka, Marly Monteiro de Carvalho, and Steve Evans (July 2018). "Business models and supply chains for the circular economy". In: *Journal of Cleaner Production* 190, pp. 712–721. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2018.04.159. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652618311867?via%3Dihub (cit. on p. 21).

Ghaffour, Noreddine, Thomas M Missimer, and Gary L Amy (2013). "Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability". In: *Desalination* 309, pp. 197–207. ISSN: 0011-9164. DOI: https://doi.org/10.1016/j.desal.2012.10.015. URL: https://www.sciencedirect.com/science/article/abs/pii/S0011916412005723?via%3Dihub (cit. on p. 225).

Ghenai, Chaouki, Mona Albawab, and Maamar Bettayeb (Feb. 2020). "Sustainability indicators for renewable energy systems using multi-criteria decision-making model and extended SWARA/ARAS hybrid method". In: *Renewable Energy* 146, pp. 580–597. ISSN: 0960-1481. DOI: 10.1016/

J.RENENE.2019.06.157. URL: https://www.sciencedirect.com/science/article/abs/pii/S0960148119309978 (cit. on p. 23).

Giugliano, Michele, Stefano Cernuschi, Mario Grosso, and Lucia Rigamonti (Sept. 2011). “Material and energy recovery in integrated waste management systems. An evaluation based on life cycle assessment”. In: *Waste Management* 31 (9-10), pp. 2092–2101. ISSN: 0956053X. DOI: 10.1016/j.wasman.2011.02.029. URL: https://www.sciencedirect.com/science/article/abs/pii/S0956053X11001140?via%3Dihub (cit. on pp. 14, 163).

Gungor, Bogachan and Ibrahim Dincer (Aug. 2021). “Development of a sustainable community with an integrated renewable and waste to energy system for multiple useful outputs”. In: *Journal of Cleaner Production* 312, p. 127704. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2021.127704. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652621019223?via%3Dihub (cit. on p. 20).

Gunnarsdottir, I, B Davidsdottir, E Worrell, and S Sigurgeirsdottir (2022). “Indicators for sustainable energy development: An Icelandic case study”. In: *Energy Policy* 164, p. 112926. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2022.112926. URL: https://www.sciencedirect.com/science/article/pii/S0301421522001513 (cit. on pp. 23, 168).

Haas, Reinhard, Nebojsa Nakicenovic, Amela Ajanovic, Thomas Faber, Lukas Kranzl, Andreas Müller, and Gustav Resch (Nov. 2008). “Towards sustainability of energy systems: A primer on how to apply the concept of energy services to identify necessary trends and policies”. In: *Energy Policy* 36 (11), pp. 4012–4021. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2008.06.028. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421508003017?via%3Dihub (cit. on p. 165).

Hadad, Eden, Erez Fershtman, Zohar Gal, Ido Silberman, and Gideon Oron (May 2022). “Simulation of dual systems of greywater reuse in high-rise buildings for energy recovery and potential use in irrigation”. In: *Resources, Conservation and Recycling* 180, p. 106134. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2021.106134. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344921007424?via%3Dihub (cit. on p. 18).

Hahnel, Ulf J.J., Mario Herberz, Alejandro Pena-Bello, David Parra, and Tobias Brosch (Feb. 2020). "Becoming prosumer: Revealing trading preferences and decision-making strategies in peer-to-peer energy communities". In: *Energy Policy* 137, p. 111098. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2019.111098. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421519306858?via%3Dihub (cit. on p. 19).

Hák, Tomáš, Svatava Janoušková, and Bedřich Moldan (2016). "Sustainable Development Goals: A need for relevant indicators". In: *Ecological Indicators* 60, pp. 565–573. ISSN: 1470-160X. DOI: https://doi.org/10.1016/j.ecolind.2015.08.003. URL: https://www.sciencedirect.com/science/article/pii/S1470160X15004240 (cit. on p. 25).

Hamiche, Ait Mimoune, Amine Boudghene Stambouli, and Samir Flazi (2016). "A review of the water-energy nexus". In: *Renewable and Sustainable Energy Reviews* 65, pp. 319–331. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2016.07.020. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032116303471?via%3Dihub (cit. on p. 31).

Heyes, Graeme, Maria Sharmina, Joan Manuel F. Mendoza, Alejandro Gallego-Schmid, and Adisa Azapagic (Mar. 2018). "Developing and implementing circular economy business models in service-oriented technology companies". In: *Journal of Cleaner Production* 177, pp. 621–632. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2017.12.168. URL: https://www.sciencedirect.com/science/article/pii/S0959652617331396?via%3Dihub (cit. on p. 21).

Hilpert, S, C Kaldemeyer, U Krien, S Günther, C Wingenbach, and G Plessmann (2018). "The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling". In: *Energy Strategy Reviews* 22, pp. 16–25. ISSN: 2211-467X. DOI: https://doi.org/10.1016/j.esr.2018.07.001. URL: https://www.sciencedirect.com/science/article/pii/S2211467X18300609 (cit. on pp. 32, 168).

Hollberg, Alexander, Thomas Lützkendorf, and Guillaume Habert (Apr. 2019). "Top-down or bottom-up? – How environmental benchmarks can support the design process". In: *Building and Environment* 153, pp. 148–157. ISSN: 0360-1323. DOI: 10.1016/J.BUILDENV.2019.02.026.

URL: https://www.sciencedirect.com/science/article/abs/pii/S0360132319301295 (cit. on p. 24).

Hong, Jinglan, Jingmin Hong, Masahiro Otaki, and Olivier Jolliet (Feb. 2009). "Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan". In: *Waste Management* 29 (2), pp. 696–703. ISSN: 0956053X. DOI: 10.1016/j.wasman.2008.03.026. URL: https://www.sciencedirect.com/science/article/abs/pii/S0956053X08001591?via%3Dihub (cit. on p. 14).

Al-Husseini, Tayseer H, Riyad H Al-Anbari, and Abdul Hameed M J AL-Obaidy (2021). "Greywater Environmental Management: A Review". In: *IOP Conference Series: Earth and Environmental Science* 779 (1), p. 012100. ISSN: 1755-1307. DOI: 10.1088/1755-1315/779/1/012100. URL: http://dx.doi.org/10.1088/1755-1315/779/1/012100 (cit. on p. 17).

Islam, K. M.Nazmul and Mohammed Jashimuddin (Feb. 2017). "Reliability and economic analysis of moving towards wastes to energy recovery based waste less sustainable society in Bangladesh: The case of commercial capital city Chittagong". In: *Sustainable Cities and Society* 29, pp. 118–129. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2016.11.011. URL: https://www.sciencedirect.com/science/article/pii/S2210670716306746 (cit. on p. 22).

Al-Jayyousi, Odeh R. (Aug. 2003). "Greywater reuse: towards sustainable water management". In: *Desalination* 156 (1-3), pp. 181–192. ISSN: 0011-9164. DOI: 10.1016/S0011-9164(03)00340-0. URL: https://www.sciencedirect.com/science/article/abs/pii/S0011916403003400?via%3Dihub (cit. on p. 16).

Johannsen, Rasmus Magni, Poul Alberg Östergaard, David Maya-Drysdale, and Louise Krog Elmegaard Mouritsen (2021). "Designing Tools for Energy System Scenario Making in Municipal Energy Planning". In: *Energies* 14 (5). ISSN: 1996-1073. DOI: 10.3390/en14051442. URL: https://www.mdpi.com/1996-1073/14/5/1442 (cit. on p. 20).

Jossin, Jasmin and Oliver Peters (Jan. 2022). "Sustainable Development Goals (SDG) indicators for municipalities: a comprehensive monitoring approach from Germany". In: *Journal of Urban Ecology* 8 (1), juac020. ISSN: 2058-5543. DOI: 10.1093/jue/juac020. URL: https://doi.org/10.1093/jue/juac020 (cit. on pp. 26, 123).

Kavvadias, Konstantinos C and Sylvain Quoilin (2018). "Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment". In: *Applied Energy* 216, pp. 452–465. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2018.02.080. URL: https://www.sciencedirect.com/science/article/pii/S0306261918302058 (cit. on p. 248).

Khajvand, Mahdieh, Ali Khosravanipour Mostafazadeh, Patrick Drogui, Rajeshwar Dayal Tyagi, and Emmanuel Brien (2022). "Greywater characteristics, impacts, treatment, and reclamation using adsorption processes towards the circular economy". In: *Environmental Science and Pollution Research* 29 (8), pp. 10966–11003. ISSN: 1614-7499. DOI: 10.1007/s11356-021-16480-z. URL: https://doi.org/10.1007/s11356-021-16480-z (cit. on p. 16).

Khan, Shamshad, Raheel Anjum, Syed Turab Raza, Nazir Ahmed Bazai, and Muhammad Ihtisham (Feb. 2022). "Technologies for municipal solid waste management: Current status, challenges, and future perspectives". In: *Chemosphere* 288, p. 132403. ISSN: 0045-6535. DOI: 10.1016/J.CHEMOSPHERE.2021.132403. URL: https://www.sciencedirect.com/science/article/abs/pii/S0045653521028757?via%3Dihub (cit. on pp. 15, 20).

Kılkış, Şiir (Apr. 2019). "Benchmarking the sustainability of urban energy, water and environment systems and envisioning a cross-sectoral scenario for the future". In: *Renewable and Sustainable Energy Reviews* 103, pp. 529–545. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2018.11.006. URL: https://www.sciencedirect.com/science/article/abs/pii/S136403211830738X (cit. on p. 24).

Klemm, Christian and Frauke Wiese (2022). "Indicators for the optimization of sustainable urban energy systems based on energy system modeling". In: *Energy, Sustainability and Society* 12 (1), p. 3. ISSN: 2192-0567. DOI: 10.1186/s13705-021-00323-3. URL: https://doi.org/10.1186/s13705-021-00323-3 (cit. on pp. 24, 167).

Knickmeyer, Doris (Feb. 2020). "Social factors influencing household waste separation: A literature review on good practices to improve the recycling performance of urban areas". In: *Journal of Cleaner Production* 245, p. 118605. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2019.118605.

URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652619334754?via%3Dihub (cit. on p. 164).

Knutsson, J and P Knutsson (2021). "Water and energy savings from greywater reuse: a modelling scheme using disaggregated consumption data". In: *International Journal of Energy and Water Resources* 5 (1), pp. 13–24. ISSN: 2522-0101. DOI: 10.1007/s42108-020-00096-z. URL: https://doi.org/10.1007/s42108-020-00096-z (cit. on p. 16).

Kourkoumpas, Dimitrios Sotirios, Georgios Benekos, Nikolaos Nikolopoulos, Sotirios Karellas, Panagiotis Grammelis, and Emmanouel Kakaras (Dec. 2018). "A review of key environmental and energy performance indicators for the case of renewable energy systems when integrated with storage solutions". In: *Applied Energy* 231, pp. 380–398. ISSN: 0306-2619. DOI: 10.1016/J.APENERGY.2018.09.043. URL: https://www.sciencedirect.com/science/article/abs/pii/S0306261918313527 (cit. on p. 23).

Kubiszewski, Ida, Kenneth Mulder, Diane Jarvis, and Robert Costanza (Feb. 2022). "Toward better measurement of sustainable development and wellbeing: A small number of SDG indicators reliably predict life satisfaction". In: *Sustainable Development* 30 (1). https://doi.org/10.1002/sd.2234, pp. 139–148. ISSN: 0968-0802. DOI: https://doi.org/10.1002/sd.2234. URL: https://doi.org/10.1002/sd.2234 (cit. on p. 25).

Kumar, Amruth N and Ingrid F Russel (2000). "Introduction". In: *International Journal of Pattern Recognition and Artificial Intelligence* 14 (01), pp. 1–2. DOI: 10.1142/S0218001400000027. URL: https://www.worldscientific.com/doi/abs/10.1142/S0218001400000027 (cit. on p. 31).

Kuznetsova, Elizaveta, Michel-Alexandre Cardin, Mingzhen Diao, and Sizhe Zhang (2019). "Integrated decision-support methodology for combined centralized-decentralized waste-to-energy management systems design". In: *Renewable and Sustainable Energy Reviews* 103, pp. 477–500. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2018.12.020. URL: https://www.sciencedirect.com/science/article/pii/S1364032118308165 (cit. on p. 21).

Kylili, Angeliki, Paris A. Fokaides, and Petra Amparo Lopez Jimenez (Apr. 2016). "Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review". In: *Renewable and Sustainable Energy Reviews* 56, pp. 906–915. ISSN: 1364-

0321. DOI: 10.1016/J.RSER.2015.11.096. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032115013635 (cit. on p. 23).

Lazar, Nina and K. Chithra (Jan. 2022). "Benchmarking critical criteria for assessing sustainability of residential buildings in tropical climate". In: *Journal of Building Engineering* 45, p. 103467. ISSN: 2352-7102. DOI: 10.1016/J.JOBE.2021.103467. URL: https://www.sciencedirect.com/science/article/abs/pii/S2352710221013255 (cit. on p. 24).

Lee, Minha, Heejung Kim, Jin-Yong Lee, Jae E Yang, and Chungwan Lim (2022). "A Shift Towards Integrated and Adaptive Water Management in South Korea: Building Resilience Against Climate Change". In: *Water Resources Management* 36 (5), pp. 1611–1625. ISSN: 1573-1650. DOI: 10.1007/s11269-022-03071-x. URL: https://doi.org/10.1007/s11269-022-03071-x (cit. on p. 15).

Leigh, Nancey Green and Heonyeong Lee (2019). "Sustainable and Resilient Urban Water Systems: The Role of Decentralization and Planning". In: *Sustainability* 11 (3). ISSN: 2071-1050. DOI: 10.3390/su11030918. URL: https://www.mdpi.com/2071-1050/11/3/918 (cit. on p. 22).

Lewandowski, Mateusz (2016). "Designing the Business Models for Circular Economy—Towards the Conceptual Framework". In: *Sustainability* 8 (1). ISSN: 2071-1050. DOI: 10.3390/su8010043. URL: https://www.mdpi.com/2071-1050/8/1/43 (cit. on p. 21).

Li, Donglin, Qiting Zuo, and Zhizhou Zhang (June 2022). "A new assessment method of sustainable water resources utilization considering fairness-efficiency-security: A case study of 31 provinces and cities in China". In: *Sustainable Cities and Society* 81, p. 103839. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2022.103839. URL: https://www.sciencedirect.com/science/article/abs/pii/S2210670722001664 (cit. on p. 24).

Lichtenwoehrer, Peter, Lore Abart-Heriszt, Florian Kretschmer, Franz Suppan, Gernot Stoeglehner, and Georg Neugebauer (2021). "Evaluating Spatial Interdependencies of Sector Coupling Using Spatiotemporal Modelling". In: *Energies* 14 (5). ISSN: 1996-1073. DOI: 10.3390/en14051256. URL: https://www.mdpi.com/1996-1073/14/5/1256 (cit. on p. 18).

Liu, Fengyu, Jue Feng, Ge Zhai, and Asif Razzaq (Nov. 2022). "Influence of fiscal decentralization and renewable energy investment on ecological sustainability in EU: What is the moderating role of institutional governance?” In: *Renewable Energy* 200, pp. 1265–1274. ISSN: 0960-1481. DOI: 10.1016/J.RENENE.2022.10.036. URL: https://www.sciencedirect.com/science/article/abs/pii/S0960148122015294 (cit. on p. 21).

Lu, Yangsiyu, Yong Geng, Zhe Liu, Raymond Cote, and Xiaoman Yu (Feb. 2017). “Measuring sustainability at the community level: An overview of China’s indicator system on National Demonstration Sustainable Communities”. In: *Journal of Cleaner Production* 143, pp. 326–335. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2016.12.105. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652616321692?via%3Dihub (cit. on p. 19).

Makropoulos, Christos K and David Butler (2010). “Distributed Water Infrastructure for Sustainable Communities”. In: *Water Resources Management* 24 (11), pp. 2795–2816. ISSN: 1573-1650. DOI: 10.1007/s11269-010-9580-5. URL: https://doi.org/10.1007/s11269-010-9580-5 (cit. on p. 20).

Maldet, Matthias, Georg Lettner, Christoph Loschan, Daniel Schwabeneder, and Hans Auer (2023a). “Creating an indicator system for the United Nations Sustainable Development Goals in communities and municipalities: Application and analysis in an Austrian case study”. In: *Heliyon* 9.8, e19010. ISSN: 2405-8440. DOI: https://doi.org/10.1016/j.heliyon.2023.e19010. URL: https://www.sciencedirect.com/science/article/pii/S2405844023062187 (cit. on pp. 5–9, 11, 13, 121).

Maldet, Matthias, Christoph Loschan, Daniel Schwabeneder, Georg Lettner, and Hans Auer (2023b). “Business models for local energy market and circular economy establishment in municipalities: A case study in an Austrian municipality”. In: *Heliyon (forthcoming)* (cit. on pp. 5–7, 9, 11, 13, 85).

Maldet, Matthias, Frida Huglen Revheim, Daniel Schwabeneder, Georg Lettner, Pedro Crespo del Granado, Aziz Saif, Markus Löschenbrand, and Shafi Khadem (July 2022a). “Trends in local electricity market design: Regulatory barriers and the role of grid tariffs”. In: *Journal of Cleaner Production* 358, p. 131805. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2022.131805. URL: https://www.sciencedirect.com/science/article/pii/S0959652622014159?via%3Dihub (cit. on pp. 4, 165).

Maldet, Matthias, Daniel Schwabeneder, Georg Lettner, Christoph Loschan, Carlo Corinaldesi, and Hans Auer (2022b). "Beyond Traditional Energy Sector Coupling: Conserving and Efficient Use of Local Resources". In: *Sustainability* 14 (12). ISSN: 2071-1050. DOI: 10.3390/su14127445. URL: https://www.mdpi.com/2071-1050/14/12/7445 (cit. on pp. 4–6, 9, 10, 13, 20, 31, 49–51, 92, 129, 131, 240, 253).

Maldet, Matthias, Daniel Schwabeneder, Georg Lettner, Christoph Loschan, Carlo Corinaldesi, and Hans Auer (2023c). "Local sustainable communities: sector coupling and community optimization in decentralized energy systems". In: *Cleaner Energy Systems (under review)* (cit. on pp. 5, 6, 9, 10, 13, 47).

Mandal, Deepika, Pawan Labhasetwar, Shankar Dhone, Ajay Shankar Dubey, Gangadhar Shinde, and Satish Wate (Jan. 2011). "Water conservation due to greywater treatment and reuse in urban setting with specific context to developing countries". In: *Resources, Conservation and Recycling* 55 (3), pp. 356–361. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2010.11.001. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344910002399?via%3Dihub (cit. on p. 16).

Masuda, Shuhei, Itsumi Sano, Toshimasa Hojo, Yu You Li, and Osamu Nishimura (Feb. 2018). "The comparison of greenhouse gas emissions in sewage treatment plants with different treatment processes". In: *Chemosphere* 193, pp. 581–590. ISSN: 18791298. DOI: 10.1016/j.chemosphere.2017.11.018. URL: https://www.sciencedirect.com/science/article/abs/pii/S004565351731785X?via%3Dihub (cit. on p. 14).

Medina-Mijangos, Rubí and Luis Seguí-Amórtegui (Jan. 2021). "Technical-economic analysis of a municipal solid waste energy recovery facility in Spain: A case study". In: *Waste Management* 119, pp. 254–266. ISSN: 0956-053X. DOI: 10.1016/J.WASMAN.2020.09.035. URL: https://www.sciencedirect.com/science/article/abs/pii/S0956053X20305468?via%3Dihub (cit. on p. 15).

Mesjasz-Lech, Agata (2021). "Municipal Urban Waste Management - Challenges for Polish Cities in an Era of Circular Resource Management". In: *Resources* 10 (6). ISSN: 2079-9276. DOI: 10.3390/resources10060055. URL: https://www.mdpi.com/2079-9276/10/6/55 (cit. on p. 22).

Michailos, Stavros, Mark Walker, Adam Moody, Davide Poggio, and Mohamed Pourkashanian (Feb. 2021). "A techno-economic assessment of implementing power-to-gas systems based on biomethanation in an operating waste water treatment plant". In: *Journal of Environmental Chemical Engineering* 9 (1), p. 104735. ISSN: 2213-3437. DOI: 10.1016/J.JECE.2020.104735. URL: https://www.sciencedirect.com/science/article/abs/pii/S2213343720310848?via%3Dihub (cit. on p. 18).

Mills, N., P. Pearce, J. Farrow, R. B. Thorpe, and N. F. Kirkby (Jan. 2014). "Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies". In: *Waste Management* 34 (1), pp. 185–195. ISSN: 0956053X. DOI: 10.1016/j.wasman.2013.08.024. URL: https://www.sciencedirect.com/science/article/pii/S0956053X13003978?via%3Dihub (cit. on p. 18).

Milutinović, Biljana, Gordana Stefanović, Petar S. Đekić, Ivan Mijailović, and Mladen Tomić (Oct. 2017). "Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multi-criteria analysis". In: *Energy* 137, pp. 917–926. ISSN: 03605442. DOI: 10.1016/j.energy.2017.02.167. URL: https://www.sciencedirect.com/science/article/abs/pii/S0360544217303493 (cit. on pp. 14, 17, 22).

Miola, Apollonia and Fritz Schiltz (Oct. 2019). "Measuring sustainable development goals performance: How to monitor policy action in the 2030 Agenda implementation?" In: *Ecological Economics* 164, p. 106373. ISSN: 0921-8009. DOI: 10.1016/J.ECOLECON.2019.106373. URL: https://www.sciencedirect.com/science/article/pii/S092180091930103X (cit. on p. 25).

Mischen, Pamela A, George C Homsy, Carl P Lipo, Robert Holahan, Valerie Imbruce, Andreas Pape, Weixing Zhu, Joseph Graney, Ziang Zhang, Louisa M Holmes, and Manuel Reina (2019). "A Foundation for Measuring Community Sustainability". In: *Sustainability* 11 (7). ISSN: 2071-1050. DOI: 10.3390/su11071903. URL: https://www.mdpi.com/2071-1050/11/7/1903 (cit. on p. 25).

Mokhtara, Charafeddine, Belkhir Negrou, Noureddine Settou, Bouferrouk Abdessalem, and Yufeng Yao (Oct. 2020). "Design optimization of grid-connected PV-Hydrogen for energy prosumers considering sector-coupling paradigm: Case study of a University building in Algeria".

In: *International Journal of Hydrogen Energy* 46. DOI: 10.1016/j.ijhydene.2020.10.069. URL: https://www.sciencedirect.com/science/article/abs/pii/S0360319920338660?via%3Dihub (cit. on p. 17).

Mongird, Kendall, Vilayanur Viswanathan, Patrick Balducci, Jan Alam, Vanshika Fotedar, Vladimir Koritarov, and Boualem Hadjerioua (2020). "An Evaluation of Energy Storage Cost and Performance Characteristics". In: *Energies* 13 (13). ISSN: 1996-1073. DOI: 10.3390/en13133307. URL: https://www.mdpi.com/1996-1073/13/13/3307 (cit. on p. 225).

Morris, Anthony, Jian Zuo, Yutao Wang, and Jiayuan Wang (Feb. 2018). "Readiness for sustainable community: A case study of Green Star Communities". In: *Journal of Cleaner Production* 173, pp. 308–317. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2017.03.190. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652617306546?via%3Dihub (cit. on p. 19).

Moschen, Suane A, Janaina Macke, Suélen Bebber, and Marcelo Benetti Correa da Silva (Jan. 2019). "Sustainable development of communities: ISO 37120 and UN goals". In: *International Journal of Sustainability in Higher Education* 20 (5), pp. 887–900. ISSN: 1467-6370. DOI: 10.1108/IJSHE-01-2019-0020. URL: https://doi.org/10.1108/IJSHE-01-2019-0020 (cit. on p. 26).

Mourad, Khaldoon A., Justyna C. Berndtsson, and Ronny Berndtsson (Oct. 2011). "Potential fresh water saving using greywater in toilet flushing in Syria". In: *Journal of Environmental Management* 92 (10), pp. 2447–2453. ISSN: 0301-4797. DOI: 10.1016/J.JENVMAN.2011.05.004. URL: https://www.sciencedirect.com/science/article/abs/pii/S030147971100140X?via%3Dihub (cit. on p. 17).

Moya, Diego, Clay Aldás, Germánico López, and Prasad Kaparaju (Oct. 2017). "Municipal solid waste as a valuable renewable energy resource: a worldwide opportunity of energy recovery by using Waste-To-Energy Technologies". In: *Energy Procedia* 134, pp. 286–295. ISSN: 1876-6102. DOI: 10.1016/J.EGYPRO.2017.09.618. URL: https://www.sciencedirect.com/science/article/pii/S187661021734763X?via%3Dihub (cit. on pp. 14, 17, 22).

Namany, Sarah, Tareq Al-Ansari, and Rajesh Govindan (July 2019). "Sustainable energy, water and food nexus systems: A focused review of decision-making tools for efficient resource management and governance". In: *Journal of Cleaner Production* 225, pp. 610–626. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2019.03.304. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652619310200?via%3Dihub (cit. on p. 20).

Neugebauer, Georg, Peter Lichtenwoehrer, Franz Huber, Gernot Stoeglehner, and Florian Kretschmer (2022). "Potentials and Integrated Suitability Pre-assessment of Wastewater Treatment Plants as Local Energy Cells". In: *Frontiers in Environmental Science* 9. ISSN: 2296-665X. DOI: 10.3389/fenvs.2021.785557. URL: https://www.frontiersin.org/article/10.3389/fenvs.2021.785557 (cit. on p. 18).

Neves, Ana Rita and Vítor Leal (Dec. 2010). "Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework". In: *Renewable and Sustainable Energy Reviews* 14 (9), pp. 2723–2735. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2010.07.067. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032110002479 (cit. on p. 24).

Ngan, Sue Lin, Bing Shen How, Sin Yong Teng, Michael Angelo B. Promentilla, Puan Yatim, Ah Choy Er, and Hon Loong Lam (Sept. 2019). "Prioritization of sustainability indicators for promoting the circular economy: The case of developing countries". In: *Renewable and Sustainable Energy Reviews* 111, pp. 314–331. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2019.05.001. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032119303077 (cit. on p. 23).

Ni, L., S. K. Lau, H. Li, T. Zhang, J. S. Stansbury, Jonathan Shi, and Jill Neal (June 2012). "Feasibility study of a localized residential grey water energy-recovery system". In: *Applied Thermal Engineering* 39, pp. 53–62. ISSN: 1359-4311. DOI: 10.1016/J.APPLTHERMALENG.2012.01.031. URL: https://www.sciencedirect.com/science/article/abs/pii/S1359431112000403?via%3Dihub (cit. on p. 18).

Nie, Jinzhe, Zan Li, Xiangrui Kong, and Deying Li (2017). "Analysis and Comparison Study on Different HFC Refrigerants for Space Heating Air Source Heat Pump in Rural Residential Buildings of North China". In: *Procedia Engineering* 205, pp. 1201–1206. ISSN: 1877-7058. DOI: https://doi.org/10.1016/j.proeng.2017.10.354. URL: https://www.s ciencedirect.com/science/article/pii/S1877705817350294?via%3Dihub (cit. on pp. 225, 247).

Nolde, Erwin (Dec. 2000). "Greywater reuse systems for toilet flushing in multi-storey buildings – over ten years experience in Berlin". In: *Urban Water* 1 (4), pp. 275–284. ISSN: 1462-0758. DOI: 10.1016/S1462-0758(00)00023-6. URL: https://www.sciencedirect.com/science/article/abs/pii/S1462075800000236?via%3Dihub (cit. on p. 16).

Nouri, Narjes, Farhad Balali, Adel Nasiri, Hamid Seifoddini, and Wilkistar Otieno (Aug. 2019). "Water withdrawal and consumption reduction for electrical energy generation systems". In: *Applied Energy* 248, pp. 196–206. ISSN: 03062619. DOI: 10.1016/j.apenergy.2019.04.023. URL: https://www.sciencedirect.com/science/article/abs/pii/S0306261919306555?via%3Dihub (cit. on p. 18).

Ohnishi, Satoshi, Minoru Fujii, Makoto Ohata, Inaba Rokuta, and Tsuyoshi Fujita (Jan. 2018). "Efficient energy recovery through a combination of waste-to-energy systems for a low-carbon city". In: *Resources, Conservation and Recycling* 128, pp. 394–405. ISSN: 18790658. DOI: 10.1016/j.resconrec.2016.11.018. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344916303433?via%3Dihub (cit. on pp. 17, 22).

Oladejo, Jumoke, Kaiqi Shi, Xiang Luo, Gang Yang, and Tao Wu (2019). "A Review of Sludge-to-Energy Recovery Methods". In: *Energies* 12 (1). ISSN: 1996-1073. DOI: 10.3390/en12010060. URL: https://www.mdpi.com/1996-1073/12/1/60 (cit. on p. 31).

Otaki, Yurina, Kazuhiro Ueda, and Osamu Sakura (Feb. 2017). "Effects of feedback about community water consumption on residential water conservation". In: *Journal of Cleaner Production* 143, pp. 719–730. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2016.12.051. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652616321060?via%3Dihub (cit. on p. 21).

Peccia, Jordan and Paul Westerhoff (July 2015). "We Should Expect More out of Our Sewage Sludge". In: *Environmental Science & Technology* 49 (14). doi: 10.1021/acs.est.5b01931, pp. 8271–8276. ISSN: 0013-936X. DOI: 10.1021/acs.est.5b01931. URL: https://pubs.acs.org/doi/10.1021/acs.est.5b01931 (cit. on pp. 3, 14).

Periathamby, Agamuthu (Jan. 2011). "Municipal Waste Management". In: *Waste*, pp. 109–125. DOI: 10.1016/B978-0-12-381475-3.10008-7. URL: https://www.sciencedirect.com/science/article/pii/B9780123814753100087 (cit. on p. 22).

Piasecki, Adam (2019). "Water and Sewage Management Issues in Rural Poland". In: *Water* 11 (3). ISSN: 2073-4441. DOI: 10.3390/w11030625. URL: https://www.mdpi.com/2073-4441/11/3/625 (cit. on p. 22).

Pujara, Yash, Pankaj Pathak, Archana Sharma, and Janki Govani (Oct. 2019). "Review on Indian Municipal Solid Waste Management practices for reduction of environmental impacts to achieve sustainable development goals". In: *Journal of Environmental Management* 248, p. 109238. ISSN: 0301-4797. DOI: 10.1016/J.JENVMAN.2019.07.009. URL: https://www.sciencedirect.com/science/article/pii/S0301479719309405 (cit. on p. 25).

Puttachai, Wachirawit, Payap Tarkhamtham, Woraphon Yamaka, and Paravee Maneejuk (Sept. 2021). "Linear and nonlinear causal relationships between waste-to-energy and energy consumption in Germany". In: *Energy Reports* 7, pp. 286–292. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2021.06.047. URL: https://www.sciencedirect.com/science/article/pii/S2352484721004121?via%3Dihub (cit. on p. 17).

Qadi, Shireen Al, Behzad Sodagar, and Amira Elnokaly (Sept. 2018). "Estimating the heating energy consumption of the residential buildings in Hebron, Palestine". In: *Journal of Cleaner Production* 196, pp. 1292–1305. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2018.06.059. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652618317098?via%3Dihub (cit. on p. 226).

Quan, Le Minh, Hesam Kamyab, Ali Yuzir, Veeramuthu Ashokkumar, Seyed Ehsan Hosseini, Balamuralikrishnan Balasubramanian, and Irina Kirpichnikova (May 2022). "Review of the application of gasification and combustion technology and waste-to-energy technologies in sewage sludge treatment". In: *Fuel* 316, p. 123199. ISSN: 0016-2361. DOI: 10.1016/J.FUEL.2022.123199. URL: https://www.sciencedirect.com/science/article/abs/pii/S0016236122000709?via%3Dihub (cit. on p. 14).

Radingoana, Makgalake P., Timothy Dube, and Dominic Mazvimavi (Apr. 2020). "Progress in greywater reuse for home gardening: Opportunities, perceptions and challenges". In: *Physics and Chemistry of the Earth,* *Parts A/B/C* 116, p. 102853. ISSN: 1474-7065. DOI: 10.1016/J.PCE.2020.102853. URL: https://www.sciencedirect.com/science/article/abs/pii/S1474706519300300?via%3Dihub (cit. on p. 16).

Ramsebner, Jasmine, Reinhard Haas, Amela Ajanovic, and Martin Wietschel (2021). “The sector coupling concept: A critical review”. In: *WIREs Energy and Environment* 10.4, e396. DOI: https://doi.org/10.1002/wene.396. eprint: https://wires.onlinelibrary.wiley.com/doi/pdf/10.1002/wene.396. URL: https://wires.onlinelibrary.wiley.com/doi/abs/10.1002/wene.396 (cit. on p. 13).

Ranta, Valtteri, Leena Aarikka-Stenroos, and Saku J. Mäkinen (Nov. 2018). “Creating value in the circular economy: A structured multiple-case analysis of business models”. In: *Journal of Cleaner Production* 201, pp. 988–1000. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2018.08.072. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652618324089?via%3Dihub (cit. on p. 21).

Razali, Fitriyah, Dzurllkanian Daud, Choong Weng-Wai, and Wilson Rangga Anthony Jiram (Oct. 2020). “Waste separation at source behaviour among Malaysian households: The Theory of Planned Behaviour with moral norm”. In: *Journal of Cleaner Production* 271, p. 122025. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2020.122025. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652620320722 (cit. on p. 25).

Razmjoo, A. Armin, Andreas Sumper, and Afshin Davarpanah (Nov. 2019). “Development of sustainable energy indexes by the utilization of new indicators: A comparative study”. In: *Energy Reports* 5, pp. 375–383. ISSN: 2352-4847. DOI: 10.1016/J.EGYR.2019.03.006. URL: https://www.sciencedirect.com/science/article/pii/S2352484719300368 (cit. on p. 23).

Reis, Inês F.G., Ivo Gonçalves, Marta A.R. Lopes, and Carlos Henggeler Antunes (July 2021). “Business models for energy communities: A review of key issues and trends”. In: *Renewable and Sustainable Energy Reviews* 144, p. 111013. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2021.111013. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032121003038?via%3Dihub (cit. on p. 19).

Rizos, Vasileios, Arno Behrens, Wytze der Gaast, Erwin Hofman, Anastasia Ioannou, Terri Kafyeke, Alexandros Flamos, Roberto Rinaldi, Sotiris

Papadelis, Martin Hirschnitz-Garbers, and Corrado Topi (2016). "Implementation of Circular Economy Business Models by Small and Medium-Sized Enterprises (SMEs): Barriers and Enablers". In: *Sustainability* 8 (11). ISSN: 2071-1050. DOI: 10.3390/su8111212. URL: https://www.mdpi.com/2071-1050/8/11/1212 (cit. on p. 21).

Rodrigues, A. P., M. L. Fernandes, M. F.F. Rodrigues, S. C. Bortoluzzi, S. E. Gouvea da Costa, and E. Pinheiro de Lima (June 2018). "Developing criteria for performance assessment in municipal solid waste management". In: *Journal of Cleaner Production* 186, pp. 748–757. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2018.03.067. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652618307248 (cit. on p. 24).

Roth, Jonathan and Ram Rajagopal (June 2018). "Benchmarking building energy efficiency using quantile regression". In: *Energy* 152, pp. 866–876. ISSN: 0360-5442. DOI: 10.1016/J.ENERGY.2018.02.108. URL: https://www.sciencedirect.com/science/article/abs/pii/S0360544218303360 (cit. on p. 24).

Safarzadeh, Soroush, Morteza Rasti-Barzoki, and Seyed Reza Hejazi (2020). "A review of optimal energy policy instruments on industrial energy efficiency programs, rebound effects, and government policies". In: *Energy Policy* 139, p. 111342. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2020.111342. URL: https://www.sciencedirect.com/science/article/pii/S0301421520300999 (cit. on p. 23).

Santasmasas, Carme, Miquel Rovira, Frederic Clarens, and César Valderrama (Mar. 2013). "Grey water reclamation by decentralized MBR prototype". In: *Resources, Conservation and Recycling* 72, pp. 102–107. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2013.01.004. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344913000050?via%3Dihub (cit. on p. 16).

Santillan, Mary Rose, Jung Whan Syn, Saeid Charani Shandiz, Yubin Huang, Marina de Lacerda, and Behzad Rismanchi (2022). "A Technology Assessment Approach for Achieving Sustainable Communities: An Energy Master Plan for a New Urban Development". In: *Applied Sciences* 12 (8). ISSN: 2076-3417. DOI: 10.3390/app12083860. URL: https://www.mdpi.com/2076-3417/12/8/3860 (cit. on p. 19).

Sapkota, Mukta, Meenakshi Arora, Hector Malano, Magnus Moglia, Ashok Sharma, Biju George, and Francis Pamminger (2015). "An Overview of Hybrid Water Supply Systems in the Context of Urban Water Management: Challenges and Opportunities". In: *Water* 7 (1), pp. 153–174. ISSN: 2073-4441. DOI: 10.3390/w7010153. URL: https://www.mdpi.com/2073-4441/7/1/153 (cit. on p. 21).

Sarkar, Prabir, Bhaanuj Sharma, and Ural Malik (Sept. 2014). "Energy generation from grey water in high raised buildings: The case of India". In: *Renewable Energy* 69, pp. 284–289. ISSN: 0960-1481. DOI: 10.1016/J.RENENE.2014.03.046. URL: https://www.sciencedirect.com/science/article/abs/pii/S0960148114002109?via%3Dihub (cit. on p. 18).

Sayegh, Marderos Ara, Agnieszka Ludwińska, Krzysztof Rajski, and Edyta Dudkiewicz (Mar. 2021). "Environmental and energy saving potential from greywater in hotels". In: *Science of The Total Environment* 761, p. 143220. ISSN: 0048-9697. DOI: 10.1016/J.SCITOTENV.2020.143220. URL: https://www.sciencedirect.com/science/article/abs/pii/S0048969720367516?via%3Dihub (cit. on p. 18).

Schäfer, Michael, Oliver Gretzschel, and Heidrun Steinmetz (2020). "The Possible Roles of Wastewater Treatment Plants in Sector Coupling". In: *Energies* 13 (8). ISSN: 1996-1073. DOI: 10.3390/en13082088. URL: https://www.mdpi.com/1996-1073/13/8/2088 (cit. on p. 17).

Schoor, Tineke Van Der and Bert Scholtens (Mar. 2015). "Power to the people: Local community initiatives and the transition to sustainable energy". In: *Renewable and Sustainable Energy Reviews* 43, pp. 666–675. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2014.10.089. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032114009149?via%3Dihub (cit. on p. 19).

Schweizer-Ries, Petra (Nov. 2008). "Energy sustainable communities: Environmental psychological investigations". In: *Energy Policy* 36 (11), pp. 4126–4135. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2008.06.021. URL: https://www.sciencedirect.com/science/article/abs/pii/S030142150800311X?via%3Dihub (cit. on p. 19).

Seyranian, Viviane, Gale M. Sinatra, and Morgan S. Polikoff (Mar. 2015). "Comparing communication strategies for reducing residential water consumption". In: *Journal of Environmental Psychology* 41, pp. 81–90. ISSN:

0272-4944. DOI: 10.1016/J.JENVP.2014.11.009. URL: https://www.sciencedirect.com/science/article/abs/pii/S0272494414001066?via%3Dihub (cit. on p. 21).

Sharafatmandrad, Mohsen and Azam Khosravi Mashizi (2021). "Temporal and Spatial Assessment of Supply and Demand of the Water-yield Ecosystem Service for Water Scarcity Management in Arid to Semi-arid Ecosystems". In: *Water Resources Management* 35 (1), pp. 63–82. ISSN: 1573-1650. DOI: 10.1007/s11269-020-02706-1. URL: https://doi.org/10.1007/s11269-020-02706-1 (cit. on p. 15).

Si, Hongyun, Xu Duan, Wenjia Zhang, Yangyue Su, and Guangdong Wu (June 2022). "Are you a water saver? Discovering people's water-saving intention by extending the theory of planned behavior". In: *Journal of Environmental Management* 311, p. 114848. ISSN: 0301-4797. DOI: 10.1016/J.JENVMAN.2022.114848. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301479722004212?via%3Dihub (cit. on p. 20).

Silveira, Jose Luz, Celso Eduardo Tuna, and Wendell De Queiroz Lamas (Apr. 2013). "The need of subsidy for the implementation of photovoltaic solar energy as supporting of decentralized electrical power generation in Brazil". In: *Renewable and Sustainable Energy Reviews* 20, pp. 133–141. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2012.11.054. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032112006685?via%3Dihub (cit. on p. 166).

Singh, Vipin, Harish C. Phuleria, and Munish K. Chandel (Dec. 2020). "Estimation of energy recovery potential of sewage sludge in India: Waste to watt approach". In: *Journal of Cleaner Production* 276, p. 122538. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2020.122538. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652620325853?via%3Dihub (cit. on p. 14).

Siraganyan, Karni, Amarasinghage Tharindu Dasun Perera, Jean-Louis Scartezzini, and Dasaraden Mauree (2019). "Eco-Sim: A Parametric Tool to Evaluate the Environmental and Economic Feasibility of Decentralized Energy Systems". In: *Energies* 12 (5). ISSN: 1996-1073. DOI: 10.3390/en12050776. URL: https://www.mdpi.com/1996-1073/12/5/776 (cit. on p. 21).

Soong, Hui Ni, Roshartini Omar, Kai Chen Goh, and Ta Wee Seow (June 2021). "The Challenges of Implementation Greywater Recycling System In Residential Buildings". In: *Research in Management of Technology and Business* 2 (1), pp. 1113–1129. URL: https://publisher.uthm.edu.my/periodicals/index.php/rmtb/article/view/2047 (cit. on p. 17).

Sperling, Karl, Frede Hvelplund, and Brian Vad Mathiesen (Mar. 2011). "Centralisation and decentralisation in strategic municipal energy planning in Denmark". In: *Energy Policy* 39 (3), pp. 1338–1351. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2010.12.006. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421510008876 (cit. on p. 20).

St. Denis, Genevieve and Paul Parker (Oct. 2009). "Community energy planning in Canada: The role of renewable energy". In: *Renewable and Sustainable Energy Reviews* 13 (8), pp. 2088–2095. ISSN: 1364-0321. DOI: 10.1016/J.RSER.2008.09.030. URL: https://www.sciencedirect.com/science/article/abs/pii/S1364032108001767 (cit. on p. 20).

Stang, Shannon, Masoumeh Khalkhali, Marek Petrik, Michael Palace, Zhongming Lu, and Weiwei Mo (Aug. 2021). "Spatially optimized distribution of household rainwater harvesting and greywater recycling systems". In: *Journal of Cleaner Production* 312, p. 127736. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2021.127736. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652621019545?via%3Dihub (cit. on p. 16).

Sudarsan, J S, S Vaishampayan, and V Srihari (2021). "Grey water recycling as a tangible solution to water crisis : A case study in Thiruvananthapuram, India". In: *International Journal of Energy and Water Resources* 5 (4), pp. 441–445. ISSN: 2522-0101. DOI: 10.1007/s42108-021-00116-6. URL: https://doi.org/10.1007/s42108-021-00116-6 (cit. on p. 16).

Sun, Yunpeng, Weimin Guan, Asif Razzaq, Mohsin Shahzad, and Nguyen Binh An (May 2022). "Transition towards ecological sustainability through fiscal decentralization, renewable energy and green investment in OECD countries". In: *Renewable Energy* 190, pp. 385–395. ISSN: 0960-1481. DOI: 10.1016/J.RENENE.2022.03.099. URL: https://www.sciencedirect.com/science/article/abs/pii/S0960148122003834 (cit. on pp. 4, 21).

Suthar, Surindra and Pavitra Singh (Feb. 2015). "Household solid waste generation and composition in different family size and socio-economic groups: A case study". In: *Sustainable Cities and Society* 14 (1), pp. 56–63. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2014.07.004. URL: https://www.sciencedirect.com/science/article/pii/S2210670714000821 (cit. on p. 22).

Swain, R Bali and F Yang-Wallentin (Feb. 2020). "Achieving sustainable development goals: predicaments and strategies". In: *International Journal of Sustainable Development & World Ecology* 27 (2). doi: 10.1080/13504509.2019.1692316, pp. 96–106. ISSN: 1350-4509. DOI: 10.1080/13504509.2019.1692316. URL: https://doi.org/10.1080/13504509.2019.1692316 (cit. on p. 25).

Teotia, Falti and Rohit Bhakar (2016). "Local energy markets: Concept, design and operation". In: *2016 National Power Systems Conference (NPSC)*, pp. 1–6. DOI: 10.1109/NPSC.2016.7858975. URL: https://ieeexplore.ieee.org/document/7858975 (cit. on p. 4).

Thiam, Djiby Racine (2011). "An energy pricing scheme for the diffusion of decentralized renewable technology investment in developing countries". In: *Energy Policy* 39 (7). Special Section: Renewable energy policy and development, pp. 4284–4297. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2011.04.046. URL: https://www.sciencedirect.com/science/article/pii/S0301421511003296 (cit. on p. 22).

Thormark, C. (Sept. 2001). "Conservation of energy and natural resources by recycling building waste". In: *Resources, Conservation and Recycling* 33 (2), pp. 113–130. ISSN: 0921-3449. DOI: 10.1016/S0921-3449(01)00078-7. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344901000787?via%3Dihub (cit. on p. 14).

Thornbush, Mary, Oleg Golubchikov, and Stefan Bouzarovski (Dec. 2013). "Sustainable cities targeted by combined mitigation–adaptation efforts for future-proofing". In: *Sustainable Cities and Society* 9, pp. 1–9. ISSN: 2210-6707. DOI: 10.1016/J.SCS.2013.01.003. URL: https://www.sciencedirect.com/science/article/pii/S2210670713000048 (cit. on p. 20).

Tomić, Tihomir and Daniel Rolph Schneider (Jan. 2022). ""Closing two loops"—The importance of energy recovery in the "closing the loop" approach". In: *Circular Economy and Sustainability: Volume 1: Manage-*

ment and Policy, pp. 433–455. DOI: 10.1016/B978-0-12-819817-9.00021-1. URL: https://www.sciencedirect.com/science/article/abs/pii/B9780128198179000211?via%3Dihub (cit. on p. 14).

Trigaux, D, K Allacker, and W Debacker (2021). “Environmental benchmarks for buildings: a critical literature review”. In: *The International Journal of Life Cycle Assessment* 26 (1), pp. 1–21. ISSN: 1614-7502. DOI: 10.1007/s11367-020-01840-7. URL: https://doi.org/10.1007/s11367-020-01840-7 (cit. on p. 24).

Tseng, Ming Lang, Wai Peng Wong, and Keng Lin Soh (Sept. 2018). “An overview of the substance of Resource, Conservation and Recycling”. In: *Resources, Conservation and Recycling* 136, pp. 367–375. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2018.05.010. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344918301794?via%3Dihub (cit. on p. 15).

Urbinati, Andrea, Davide Chiaroni, and Vittorio Chiesa (Dec. 2017). “Towards a new taxonomy of circular economy business models”. In: *Journal of Cleaner Production* 168, pp. 487–498. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2017.09.047. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652617320346?via%3Dihub (cit. on p. 21).

Verstraete, Willy, Pieter Van de Caveye, and Vasileios Diamantis (Dec. 2009). “Maximum use of resources present in domestic "used water"”. In: *Bioresource Technology* 100 (23), pp. 5537–5545. ISSN: 09608524. DOI: 10.1016/j.biortech.2009.05.047. URL: https://www.sciencedirect.com/science/article/abs/pii/S0960852409005641?via%3Dihub (cit. on pp. 15, 228).

Wang, Cong, Zongbao Zou, and Shidao Geng (2021). “Green Technology Investment in a Decentralized Supply Chain under Demand Uncertainty”. In: *Sustainability* 13 (7). ISSN: 2071-1050. DOI: 10.3390/su13073752. URL: https://www.mdpi.com/2071-1050/13/7/3752 (cit. on pp. 21, 167).

Wang, Kai and Evan G.R. Davies (Mar. 2018). “Municipal water planning and management with an end-use based simulation model”. In: *Environmental Modelling & Software* 101, pp. 204–217. ISSN: 1364-8152. DOI: 10.1016/J.ENVSOFT.2017.12.024. URL: https://www.sciencedirect.

com/science/article/abs/pii/S136481521730556X (cit. on pp. 21, 22).

Wang, Kehua and Toyohiko Nakakubo (Sept. 2021). "Strategy for introducing sewage sludge energy utilization systems at sewage treatment plants in large cities in Japan: A comparative assessment". In: *Journal of Cleaner Production* 316, p. 128282. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2021.128282. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652621024975?via%3Dihub (cit. on p. 14).

Welling, Sebastian and Sven-Olof Ryding (2021). "Distribution of environmental performance in life cycle assessments—implications for environmental benchmarking". In: *The International Journal of Life Cycle Assessment* 26 (2), pp. 275–289. ISSN: 1614-7502. DOI: 10.1007/s11367-020-01852-3. URL: https://doi.org/10.1007/s11367-020-01852-3 (cit. on p. 24).

Wietschel, Martin et al. (2018). "Sektorkopplung: Definition, Chancen und Herausforderungen". In: (S01/2018). urn:nbn:de:0011-n-4845758. URL: http://hdl.handle.net/10419/175374 (cit. on pp. 3, 17).

Willis, Rachelle M., Rodney A. Stewarta, Kriengsak Panuwatwanich, Sarah Jones, and Andreas Kyriakides (Oct. 2010). "Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households". In: *Resources, Conservation and Recycling* 54 (12), pp. 1117–1127. ISSN: 0921-3449. DOI: 10.1016/J.RESCONREC.2010.03.004. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344910000686?via%3Dihub (cit. on p. 15).

Wretling, Vincent, Ulrika Gunnarsson-Östling, Christina Hörnberg, and Berit Balfors (Feb. 2018). "Strategic municipal energy planning in Sweden - Examining current energy planning practice and its influence on comprehensive planning". In: *Energy Policy* 113, pp. 688–700. ISSN: 0301-4215. DOI: 10.1016/J.ENPOL.2017.11.006. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421517307449 (cit. on p. 20).

Xuchao, Wu, Rajagopalan Priyadarsini, and Lee Siew Eang (2010). "Benchmarking energy use and greenhouse gas emissions in Singapore's hotel industry". In: *Energy Policy* 38 (8), pp. 4520–4527. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2010.04.006. URL: https://

www.sciencedirect.com/science/article/pii/S030142151000279X (cit. on p. 24).

Yaman, Cevat, Ismail Anil, and Omar Alagha (Aug. 2020). "Potential for greenhouse gas reduction and energy recovery from MSW through different waste management technologies". In: *Journal of Cleaner Production* 264, p. 121432. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2020.121432. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652620314797?via%3Dihub (cit. on p. 14).

Yazdanie, Mashael, Martin Densing, and Alexander Wokaun (Sept. 2016). "The role of decentralized generation and storage technologies in future energy systems planning for a rural agglomeration in Switzerland". In: *Energy Policy* 96, pp. 432–445. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2016.06.010. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421516302932 (cit. on p. 21).

Yi, Sora, Yong Chul Jang, and Alicia Kyoungjin An (Mar. 2018). "Potential for energy recovery and greenhouse gas reduction through waste-to-energy technologies". In: *Journal of Cleaner Production* 176, pp. 503–511. ISSN: 09596526. DOI: 10.1016/j.jclepro.2017.12.103. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652617330536?via%3Dihub (cit. on p. 14).

Zaharioiu, Anca Maria, Felicia Bucura, Roxana Elena Ionete, Florian Marin, Marius Constantinescu, and Simona Oancea (2021). "Opportunities regarding the use of technologies of energy recovery from sewage sludge". In: *SN Applied Sciences* 3 (9), p. 775. ISSN: 2523-3971. DOI: 10.1007/s42452-021-04758-3. URL: https://doi.org/10.1007/s42452-021-04758-3 (cit. on p. 14).

Zavala, Miguel Ángel López, Ricardo Castillo Vega, and Rebeca Andrea López Miranda (2016). "Potential of Rainwater Harvesting and Greywater Reuse for Water Consumption Reduction and Wastewater Minimization". In: *Water* 8 (6). ISSN: 2073-4441. DOI: 10.3390/w8060264. URL: https://www.mdpi.com/2073-4441/8/6/264 (cit. on pp. 3, 16).

Zhang, Bo, Zheng Meng, Lixiao Zhang, Xudong Sun, Tasawar Hayat, Ahmed Alsaedi, and Bashir Ahmad (May 2018). "Exergy-based systems account of national resource utilization: China 2012". In: *Resources, Conservation and Recycling* 132, pp. 324–338. ISSN: 0921-3449. DOI: 10.1016/J.RESCO

NREC.2017.05.011. URL: https://www.sciencedirect.com/science/article/abs/pii/S0921344917301428?via%3Dihub (cit. on p. 15).

Zhang, Chunbo, Mingming Hu, Francesco Di Maio, Benjamin Sprecher, Xining Yang, and Arnold Tukker (Jan. 2022). “An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe”. In: *Science of The Total Environment* 803, p. 149892. ISSN: 0048-9697. DOI: 10.1016/J.SCITOTENV.2021.149892. URL: https://www.sciencedirect.com/science/article/pii/S0048969721049676?via%3Dihub (cit. on p. 15).

Zhang, Lijun, Ambrose Njepu, and Xiaohua Xia (May 2021). “Minimum cost solution to residential energy-water nexus through rainwater harvesting and greywater recycling”. In: *Journal of Cleaner Production* 298, p. 126742. ISSN: 0959-6526. DOI: 10.1016/J.JCLEPRO.2021.126742. URL: https://www.sciencedirect.com/science/article/abs/pii/S0959652621009616?via%3Dihub (cit. on p. 16).

Zhang, Tongjun (Jan. 2020). “Methods of Improving the Efficiency of Thermal Power Plants”. In: *Journal of Physics: Conference Series* 1449, p. 12001. DOI: 10.1088/1742-6596/1449/1/012001. URL: https://iopscience.iop.org/article/10.1088/1742-6596/1449/1/012001 (cit. on p. 228).

Zhang, XiaoHong, ShiHuai Deng, Jun Wu, and Wenju Jiang (2010). “A sustainability analysis of a municipal sewage treatment ecosystem based on emergy”. In: *Ecological Engineering* 36 (5). Carbon, nutrient and metal retention in wetlands in a restoration context, pp. 685–696. ISSN: 0925-8574. DOI: https://doi.org/10.1016/j.ecoleng.2009.12.010. URL: https://www.sciencedirect.com/science/article/pii/S0925857409003565 (cit. on p. 22).

Zhao, Peitao, Yafei Shen, Shifu Ge, Zhenqian Chen, and Kunio Yoshikawa (2014). “Clean solid biofuel production from high moisture content waste biomass employing hydrothermal treatment”. In: *Applied Energy* 131, pp. 345–367. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2014.06.038. URL: https://www.sciencedirect.com/science/article/pii/S0306261914006205 (cit. on p. 171).

Zhuang, Yilin and Qiong Zhang (2015). “Evaluating Municipal Water Management Options with the Incorporation of Water Quality and Energy Consumption”. In: *Water Resources Management* 29 (1), pp. 35–61. ISSN:

1573-1650. DOI: 10.1007/s11269-014-0825-6. URL: https://doi.org/10.1007/s11269-014-0825-6 (cit. on p. 22).

Zsigraiová, Zdena, Gilberto Tavares, Viriato Semiao, and Maria de Graça Carvalho (May 2009). "Integrated waste-to-energy conversion and waste transportation within island communities". In: *Energy* 34 (5), pp. 623–635. ISSN: 0360-5442. DOI: 10.1016/J.ENERGY.2008.10.015. URL: https://www.sciencedirect.com/science/article/abs/pii/S0360544208002818?via%3Dihub (cit. on p. 20).

Other sources

Allen, Laura (2023). *Kitchen Greywater: Water Conservation Straight from the Sink*. https://www.hachettebookgroup.com/storey/kitchen-greywater-water-conservation-straight-from-the-sink/?lens=storey. Online; accessed 04 August 2023 (cit. on p. 94).

Anders bauen und wohnen (2023). *AQUALOOP - Grauwasserrecycling System 300 l/Tag für das Einfamilienhaus - Paketpreis*. URL: https://www.abwshop.de/Wassertechnik/Wasseraufbereitung/Aqualoop/Aqualoop-Systeme/AQUALOOP-Grauwasserrecycling-System-300-l/Tag-fuer-das-Einfamilienhaus-Paketpreis-96859.html?campaign=google.de (visited on 02/07/2023) (cit. on pp. 251, 255).

Beaumias, Olivier, Anne Briand, Katrin Millock, and Celine Nauges (2009). *RESIDENTIAL WATER USE: WATER CONSERVATION AND WATER QUALITY*. URL: http://www.oecd.org/env/consumption-innovation/43181277.pdf (visited on 10/04/2022) (cit. on p. 58).

Belefic, Dealim (Mar. 2022). *2022 Ultimate Distribution Transformer Losses Guide*. URL: https://daelim-electric.com/distribution-transformer-losses/#:~:text=The%20loss%20rate%20of%20distribution,loss%20is%20less%20than%201%25. (visited on 02/07/2023) (cit. on p. 247).

Bio fernwärme (2023). *Kosten*. URL: http://www.biofernwaerme.at/DE/kosten_biofernwaerme_9_DE.html (visited on 02/07/2023) (cit. on pp. 250, 255).

Bundesamt für Wirtschaft und Ausfuhrkontrolle (Nov. 2021). *Informationsblatt CO2-Faktoren*. URL: https://www.bafa.de/SharedDocs/Downlo ads/DE/Energie/eew_infoblatt_co2_faktoren_2021.pdf?__blob=publicationFile%5C&v=5 (visited on 12/21/2021) (cit. on pp. 229, 236).

Bundesministerium der Finanzen and Juris Das Rechtsportal (2023). *Suche in allen AfA-Tabellen*. URL: https://afa-tabellen.olexx-web.de/AfA-Tabellen/Suche_batterie (visited on 02/06/2023) (cit. on pp. 248, 253).

Bundesministerium für Finanzen (Jan. 2023). *Inhalt eines Energieausweises*. URL: https://www.oesterreich.gv.at/themen/bauen_wohnen_und_umwelt/wohnen/1/Seite.210460.html (visited on 02/21/2023) (cit. on p. 25).

Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (Jan. 2022). *Das Übereinkommen von Paris*. URL: https://www.oesterreich.gv.at/themen/bauen_wohnen_und_umwelt/klimaschutz/1/Seite.1000325.html (visited on 09/22/2022) (cit. on p. 1).

Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie (2023). *Europäischer Green Deal*. URL: https://www.bmk.gv.at/themen/klima_umwelt/eu_international/euop_greendeal.html (visited on 04/25/2023) (cit. on p. 2).

City of Golden (2021). URL: https://www.cityofgolden.net/live/sustainability-initiative/water-conservation/graywater-reuse/ (visited on 03/07/2022) (cit. on p. 16).

Convex (2022). *Müllverbrennungsanlage Zistersdorf Österreich*. URL: https://www.convex.at/projekte/mva-zistersdorf/ (visited on 02/07/2023) (cit. on pp. 251, 255).

Daniel, Cornelia and Florian Sattlberger (Feb. 2022). *Kosten von Photovoltaikanlagen*. URL: https://www.dachgold.at/photovoltaik-kosten/#Aufteilung_in_fixe_und_variable_Kosten_von_Solaranlagen (visited on 11/03/2022) (cit. on pp. 250, 255).

Danish Energy Agency (2016). *Technology Data Generation of Electricity and District Heating*. URL: https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and (visited on 05/08/2023) (cit. on p. 228).

Department of Water and Environmental Regulation Government of Western Australia (2022). *Greywater*. URL: https://www.water.wa.gov.au/ur ban-water/water-recycling-efficiencies/waterwise-community-toolkit/greywater (visited on 03/07/2022) (cit. on p. 16).

Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ L 328, 21.12.2018, p. 82–209 (n.d.) (cit. on pp. 4, 19, 48, 85, 113).

Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, OJ L 158, 14.6.2019, p. 125–199. (N.d.) (cit. on pp. 4, 19, 48, 85, 113).

e5 Österreich (2023). *Das e5-Programm für energieeffiziente Gemeinden.* URL: https://www.e5-gemeinden.at/e5-programm/das-e5-programm (visited on 02/21/2023) (cit. on p. 25).

Eawag Das Wasserforschungsinstitut des ETH-Bereichs (2021). *factsheet.* https://www.eawag.ch/fileadmin/Domain1/Beratung/Beratung_Wissenstransfer/Publ_Praxis/Faktenblaetter/fb_grauwasser_0221.pdf. Online; accessed 04 August 2023 (cit. on p. 94).

Eijk, Addo van der (Sept. 2022). *Does sustainable energy from waste have a future?* URL: https://www.wastematters.eu/news/does-sustainable-energy-from-waste-have-a-future (visited on 02/01/2023) (cit. on p. 116).

ENBW Fernwärme (2020). *EnBW Fernwärme – Ihr Beitrag zum Klimaschutz.* URL: https://assets.ctfassets.net/upmoejz03x66/6Axj5X3aKICQAEqvqLgxgO/71b392e2f8eca8004308f7967126b590/EnBW_Fernw__rme_Kennzahlen_2020_Bestandskundenflyer_Stand_06.04.2021.pdf (visited on 03/07/2023) (cit. on pp. 254, 257).

ESC Energy Solutions Center (2021). *6.8 Cost of CHP: Engineering and Installation Costs.* URL: https://understandingchp.com/chp-applications-guide/6-8-rules-of-thumb-for-chp-engineering-and-installation-costs/ (visited on 05/17/2021) (cit. on p. 228).

European Commission (2020a). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.* URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0299&from=DE (visited on 05/07/2021) (cit. on pp. 3, 31).

European Commission (2020b). *Questions and answers: An EU Strategy for Energy System Integration*. URL: https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_1258 (visited on 10/21/2021) (cit. on p. 3).

European Commission (May 2022a). *REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition*. URL: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131 (visited on 04/25/2023) (cit. on p. 2).

European Commission (2022b). *EU taxonomy for sustainable activities*. URL: https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en (visited on 07/31/2022) (cit. on p. 25).

European Commission (2023a). *Renewable Energy Directive*. URL: https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en (visited on 02/01/2023) (cit. on pp. 2, 85, 116, 160).

European Commission (2023b). *Sustainable development*. URL: https://policy.trade.ec.europa.eu/development-and-sustainability/sustainable-development_en (visited on 03/30/2023) (cit. on p. 2).

FOCUS Marketing Research (2022). *In den letzten Jahren hat sich Recycling bzw. Wiederverwertung von Gütern im Rahmen der Abfallwirtschaft etabliert. Welche der unten stehenden Statements beschreibt am besten Ihre persönliche Einstellung bezüglich Recycling?* URL: https://de.statista.com/statistik/daten/studie/1304250/umfrage/umfrage-zur-persoenlichen-einstellung-zum-recycling-in-oesterreich/ (visited on 05/01/2022) (cit. on p. 60).

Gemeinde Breitenau (2023). *Neuigkeiten aus Breitenau*. URL: https://www.breitenau.gv.at/ (visited on 02/06/2023) (cit. on pp. 86, 97, 140).

Global Petrol Price (2021a). *Israel Erdgaspreise*. URL: https://de.globalpetrolprices.com/Israel/natural_gas_prices/ (visited on 03/16/2022) (cit. on p. 228).

Global Petrol Price (2021b). *Strompreise*. URL: https://de.globalpetrolprices.com/electricity_prices/ (visited on 03/16/2022) (cit. on p. 225).

Gonzalez, Victoria Sanabria (Apr. 2022). *Ihr Stromverbrauch im Vergleich zum Durchschnitt: So sparen*. URL: https://stromliste.at/nuetzli che-infos/stromverbrauch (visited on 11/07/2022) (cit. on pp. 247, 257).

Grebe (2017). *Advice Notes on Anaerobic Digestion Economics for the NPA Region*. URL: https://grebeproject.eu/wp-content/uploads/2017/10/GREBE-Advice-Notes-AD.pdf (visited on 01/10/2023) (cit. on p. 251).

Heimhelden.de (2023). *Mit welchen Kosten ist beim Hallenbau zu rechnen?* URL: https://www.heimhelden.de/hallenbau-kosten (visited on 02/06/2023) (cit. on p. 251).

Huber Technology Waste Water Solutions (2021). *Stromverbrauch von Kläranlagen*. URL: https://www.huber.de/de/loesungen/energieeffizienz/grundsaetzliches/klaeranlagen.html (visited on 12/22/2021) (cit. on p. 227).

IEA (Oct. 2022). *Cumulative capacity and capital cost learning curve for vapour compression applications in the Sustainable Development Scenario, 2019-2070*. URL: https://www.iea.org/data-and-statistics/charts/cumulative-capacity-and-capital-cost-learning-curve-for-vapour-compression-applications-in-the-sustainable-development-scenario-2019-2070 (visited on 11/03/2022) (cit. on pp. 250, 255).

IEA Bioenergy (2003). *Municipal Solid Waste and its Role in Sustainability*. URL: https://www.ieabioenergy.com/wp-content/uploads/2013/10/40_IEAPositionPaperMSW.pdf (visited on 12/21/2021) (cit. on pp. 93, 229, 236, 257).

IEA Heat Pump Centre (2011). *Annex 32 economical heating and cooling systems for low energy houses, final report*. URL: https://www.aramis.admin.ch/?DocumentID=63016 (visited on 05/17/2021) (cit. on p. 225).

IKB (Jan. 2023). *Preisliste für kostenpflichtige Abfälle am Recyclinghof Roßau*. URL: https://www.ikb.at/fileadmin/user_upload/Dokumente/Abfall/Preisliste_Recyclinghof.pdf (visited on 03/02/2023) (cit. on p. 254).

Institute for Sustainable Communities (2022). *What is a Sustainable Community?* URL: https://sustain.org/about/what-is-a-sustainable-community/ (visited on 09/22/2022) (cit. on pp. 4, 47).

Intergovernmental Panel on Climate Change (2023). *SYNTHESIS REPORT OF THE IPCC SIXTH ASSESSMENT REPORT (AR6)*. English. URL:

https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf (visited on 04/25/2023) (cit. on p. 1).

International Energy Agency (2023). *CO2 Emissions in 2022*. URL: iea.org/reports/co2-emissions-in-2022 (visited on 04/25/2023) (cit. on p. 1).

Israel Central Bureau of Statistics (2022). *Number of households in Israel 2020, by household size*. URL: https://www.statista.com/statistics/1287835/number-of-households-in-israel-by-household-size/ (visited on 03/16/2022) (cit. on p. 223).

Israel Water Authority (2011). *Challenges and Solutions for the Water Sector in Israel and the Region*. URL: https://web.archive.org/web/20140828231723/http://www.water.gov.il/Hebrew/ProfessionalInfoAndData/2012/02-Israel-Water-Sector-Overall-Review.pdf (visited on 03/16/2022) (cit. on p. 227).

Jedamzik, Mirka (2022). *Wasserverbrauch im 4-Personen-Haushalt*. URL: https://www.co2online.de/energie-sparen/heizenergie-sparen/warmwasser/wasserverbrauch-4-personen-haushalt/#c157123 (visited on 11/08/2022) (cit. on pp. 233, 247, 257).

Johnson, Matthew (Apr. 2022). *Calculating wastewater treatment plant construction costs*. URL: fehrgraham.com/about-us/blog/calculating-wastewater-treatment-plant-construction-costs-fg (visited on 11/04/2022) (cit. on pp. 251, 255).

Juanico, Marcelo and Miquel Salgot (Mar. 2022). *Water reuse in the northern Mediterranean*. URL: https://www.researchgate.net/publication/228378519_WATER_REUSE_IN_THE_NORTHERN_MEDITERRANEAN (visited on 03/09/2022) (cit. on p. 39).

Kleppmann, Ferdinand (2014). *Current developments in European Waste-to-Energy*. URL: https://www.ask-eu.net/Default.asp?Menue=211&Bereich=1&SubBereich=1&KW=4&ArtikelPPV=28471 (visited on 05/08/2023) (cit. on p. 226).

Kloth, Philipp (2022a). *2022: Durchschnittlicher Energieverbrauch*. URL: https://www.energieheld.de/foerderung/energieberater/durchschnittlicher-energieverbrauch (visited on 11/08/2022) (cit. on pp. 247, 257).

Kloth, Philipp (2022b). *Kosten für PV-Stromspeicher - Wirtschaftlichkeit im Detail*. URL: https://www.energieheld.de/solaranlage/photovolt aik/stromspeicher/kosten#:~:text=Die%20Kosten%20f%C3%BCr%20einen%20Stromspeicher,meist%20um%20die%2020.400%20Euro. (visited on 02/07/2023) (cit. on pp. 250, 255).

Köppel, Wolfgang, Charlotte Degünther, and Jakob Wachsmuth (2018). *Bewertung der Vorkettenemissionen bei der Erdgasförderung in Deutschland*. URL: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-01-30_climate-change_02-2018_roadmap-gas_0.pdf (visited on 02/23/2022) (cit. on p. 229).

Kostencheck (2022). *Halle mit 100 qm: welche Kosten muss man rechnen?* URL: https://kostencheck.de/halle-100-qm-kosten (visited on 02/07/2023) (cit. on p. 251).

Landesamt für Umwelt Brandenburg (2018). *CO2-Emissionsfaktoren nach Energieträgern*. URL: https://lfu.brandenburg.de/cms/media.php/lbm1.a.3310.de/emissionsfaktoren_co2_2017.pdf (visited on 10/05/2022) (cit. on pp. 96, 231, 236, 257).

Lev-On, Miriam, Perry Lev-On, Idan Liebes, and Ofira Ayalon (2017). *Assessment of greenhouse gas emissions intensity from electricity generation in Israel Haifa Israel*. URL: https://www.neaman.org.il/EN/Assessment-greenhouse-gas-emissions-intensity-electricity-generation (visited on 02/22/2022) (cit. on p. 229).

Maldet, Matthias (2022). *RUTIS*. URL: https://gitlab.com/team-ensys/projects/maldet_energysystemmodel (visited on 04/20/2023) (cit. on pp. 31, 32, 49, 87, 129).

Ministère de l'environnement, de l'énergie et de la mer (Jan. 2017). *Forecast of electricity price in France in 2020, 2030 and 2040*. URL: https://www.statista.com/statistics/1067452/electricity-price-estimation-france/ (visited on 02/07/2023) (cit. on p. 248).

Ministry of Energy Department of Economics (2018). *Israel's Energy Sector Review for 2018*. URL: https://www.gov.il/BlobFolder/reports/energy_sector_2018/en/Review_of_energy_sector_2018.pdf (visited on 03/09/2022) (cit. on pp. 39, 223).

Ministry of Environmental Protection (2019). *Waste Facts and Figures*. URL: https://www.gov.il/en/departments/guides/waste_facts_and_figures#:~:text=The%20average%20resident%20of%20Israel,kilograms%20of%20waste%20per%20month (visited on 03/16/2022) (cit. on p. 226).

Mitsdoerffer, Ralf (2017). *Wärme- und Kältekonzepte auf Kläranlagen*. URL: https://www.gfm-ingenieure.de/fileadmin/Daten/Referenzen/Klaeranlage/Energie/Vortrag-Mitsdoerffer-20170115-mi.pdf (visited on 03/04/2022) (cit. on p. 18).

Münster, Marie, Daniel Moller Sneum, Rasmus Bramstoft, Fabian Buhler, Brian Elmegaard, Spyros Giannelos, Goran Strbac, Mathias Berger, David-Constantin Radu, Damian Elsaesser, Alexandre Oudalov, and Antonio Iliceto (Jan. 2020). *Sector Coupling: Concepts, State-of-the-art and Perspectives*. English. URL: https://www.etip-snet.eu/sector-coupling-concepts-state-art-perspectives/ (visited on 05/12/2021) (cit. on p. 13).

OECD Council (Dec. 2016). *Better Policies for 2030 An OECD Action Plan on the Sustainable Development Goals*. URL: https://www.oecd.org/dac/Better%20Policies%20for%202030.pdf (visited on 02/27/2023) (cit. on p. 26).

OECD Council (June 2017). *Measuring distance to the SDG targets*. URL: https://www.oecd.org/sdd/OECD-Measuring-Distance-to-SDG-Targets.pdf (visited on 02/27/2023) (cit. on pp. 26, 123).

Oluleye, Gbemi and Adam Hawkes (2020). *SOFC-based CHP market potential analysis*. Imperial College London. URL: http://www.demosofc.eu/wp-content/uploads/2017/10/SOFC-based-CHP-market-potential-analysis.pdf (visited on 01/10/2023) (cit. on p. 251).

Österreichs Energie (2020). *Konsultation Synthetisches Lastprofil E1 für PV*. URL: https://ebutilities.at/utilities/konsultationen/detail.php?ConsultationID=9 (visited on 11/09/2022) (cit. on p. 247).

Ouden, Bert den, Niki Lintmejer, Jort van Aken, Afman Maarten, Harry Croezen, Marit van Lieshout, Egbert Klop, René Waggeveld, and Jan Grift (2017). *Electrification in the Dutch process industry*. URL: https://blueterra.nl/wp-content/uploads/2018/03/Electrification-in-the-Dutch-process-industry-final-report.pdf (visited on 05/17/2021) (cit. on p. 226).

Paschotta, Rüdiger (2021). *Warmwasser*. URL: https://www.energie-lexikon.info/warmwasser.html (visited on 11/29/2021) (cit. on p. 226).

Ritchie, Naz and Chuck Smith (Mar. 2009). *Comparison of Greenhouse Gas Emissions from Waste-to-Energy Facilities and the Vancouver Landfill.*

URL: http://pentz.com/NoIncinerator/greenhouse%20Emmissions.pdf (visited on 12/21/2021) (cit. on pp. 229, 236).

Rosenkranz, Alexandra (2020). *Der durchschnittliche Energiebedarf im Haus.* URL: https://heizung.de/heizung/tipps/der-durchschnittliche-energiebedarf-im-haus/#:~:text=Single%2DHaushalt%3A%201.000%20bis%202.000,bis%204.500%20Kilowattstunden%20pro%20Jahr (visited on 10/04/2022) (cit. on pp. 233, 257).

Samco (May 2016). *How Much Does a Wastewater Treatment System Cost? (Pricing, Factors, Etc.)* URL: https://samcotech.com/cost-wastewater-treatment-system/ (visited on 11/04/2022) (cit. on pp. 251, 255).

Santika, W G, T Urmee, M Anissuzaman, G M Shafiullah, and P A Bahri (2018). "Sustainable energy for all: Impacts of Sustainable Development Goals implementation on household sector energy demand in Indonesia". In: pp. 13–18. DOI: 10.1109/ICSGTEIS.2018.8709108. URL: https://ieeexplore.ieee.org/document/8709108 (cit. on p. 25).

Schiermeier, Quirin (Sept. 2014). *Wasser marsch!* URL: https://www.spektrum.de/news/neue-methoden-zur-trinkwassergewinnung/1306738 (visited on 01/21/2022) (cit. on p. 225).

Schodl, Barbara (2019). *Statusbericht zu den CO2 Emissionen neu zugelassener Pkw in Österreich im Jahr 2018.* URL: https://www.bmk.gv.at/dam/jcr:9c5c0fba-a8b9-41dc-9f5e-6f839e9cb68f/CO2_Monitoring_PKW_2018.pdf (visited on 07/21/2022) (cit. on p. 236).

Scott, Sue and Dorothy Watson (May 2006). *Introduction of Weight-Based Charges for Domestic Solid Waste Disposal.* URL: https://mpra.ub.uni-muenchen.de/107713/1/MPRA_paper_107713.pdf (visited on 05/17/2022) (cit. on p. 226).

Siemens (2017). *Direct current for long-distance transmission.* URL: https://medienportal.siemens-stiftung.org/view/101614#:~:text=A%20cable%20for%20alternating%20current,are%20calculated%20per%201%2C000%20km. (visited on 02/07/2023) (cit. on p. 247).

Statistisches Bundesamt (2022). *Aufkommen von Haushaltsabfällen je Einwohner in Deutschland in den Jahren 2004 bis 2020.* URL: https://de.statista.com/statistik/daten/studie/161228/umfrage/haushaltsabfaelle-je-einwohner-seit-dem-jahr-2003/ (visited on 11/09/2022) (cit. on pp. 233, 257).

Statistik Austria (Feb. 2022). *Haushaltsprognose 2021*. URL: http://wko.at/statistik/jahrbuch/bevoelkerung-haushalte.pdf (visited on 11/07/2022) (cit. on p. 247).

Tsoukanta, Eleni (Aug. 2022). *Was kostet eine Wärmepumpe für ein Einfamilienhaus?* URL: https://www.net4energy.com/de-de/heizen/waermepumpe-kosten (visited on 11/03/2022) (cit. on pp. 250, 255).

umweltwirtschaft.com (Sept. 2022). *EU-Parlament will Nachhaltigkeitskriterien für Müllverbrennung verschärfen*. URL: https://www.umweltwirtschaft.com/news/abfallwirtschaft-und-recycling/thermische-behandlung-energetische-verwertung-beseitigung-instandhaltung/Erneuerbare-Energien-Richtlinie-EU-Parlament-will-Nachhaltigkeitskriterien-fuer-Muellverbrennung-verschaerfen-27638 (visited on 02/07/2023) (cit. on p. 116).

United Nations (2023a). *Water Scarcity*. URL: https://www.unwater.org/water-facts/water-scarcity (visited on 05/08/2023) (cit. on p. 161).

United Nations (2021). *Causes and Effects of Climate Change*. URL: https://www.un.org/en/climatechange/science/causes-effects-climate-change (visited on 10/21/2021) (cit. on p. 1).

United Nations (2022). *Do you know all 17 SDGs?* URL: https://sdgs.un.org/goals (visited on 09/22/2022) (cit. on pp. 2, 25, 76, 112, 115).

United Nations (2023b). *Transforming our world: the 2030 Agenda for Sustainable Development*. URL: https://sdgs.un.org/2030agenda (visited on 02/13/2023) (cit. on pp. 3, 25, 121, 123).

United States Environmental Protection Agency (2022). *Local Energy Efficiency Benefits and Opportunities*. Online; accessed 25 April 2023. URL: https://www.epa.gov/statelocalenergy/local-energy-efficiency-benefits-and-opportunities (cit. on p. 3).

Vähl, Janek (Sept. 2022). *Zero Waste Europe approves Parliament resolutions on RED III*. URL: https://zerowasteeurope.eu/press-release/zero-waste-europe-approves-parliament-resolutions-on-red-iii/ (visited on 02/01/2023) (cit. on pp. 116, 160).

Verein GeWoZu (2020). *Gemeinschaftlich Wohnen Die Zukunft*. URL: https://gewozu.at/ (visited on 10/04/2022) (cit. on pp. 49, 134).

Vogel, Benedikt (2018). *Wenn Kühlen wichtiger wird als Heizen*. URL: https://www.gebaeudetechnik.ch/waerme-kaelte/kaeltetechnik/kaelt eanlagen/wenn-kuehlen-wichtiger-wird-als-heizen/ (visited on 10/04/2022) (cit. on p. 233).

Weißbach, Anne (2022). *Stromverbrauch im Haushalt*. URL: https://www.co2online.de/energie-sparen/strom-sparen/strom-sparen-stromspartipps/stromverbrauch-im-haushalt/#:~:text=F%C3%BCr%20Deutschland%20gilt%3A%202%20Personen,%20Euro (visited on 10/04/2022) (cit. on pp. 233, 257).

Wien Energie (Oct. 2022). *Stromerzeugung in Österreich 2021*. URL: https://positionen.wienenergie.at/grafiken/stromerzeugung-in-osterreich/ (visited on 03/07/2023) (cit. on p. 254).

Worldometer (2015). *Israel Natural Gas*. URL: https://www.worldometers.info/gas/israel-natural-gas/ (visited on 03/16/2022) (cit. on p. 228).

Wright, Mindy (Aug. 2019). *Most Water-Stressed Countries In The World For 2019*. URL: https://ceoworld.biz/2019/08/08/most-water-stressed-countries-in-the-world-for-2019/ (visited on 03/09/2022) (cit. on p. 39).

Zablocki, Alexandra (Feb. 2019). *Fact Sheet Energy Storage (2019)*. URL: https://www.eesi.org/papers/view/energy-storage-2019#:~:text=Thermal%20energy%20storage%20can%20also,type%20of%20thermal%20energy%20used. (visited on 05/12/2021) (cit. on p. 226).

Appendices

A. Data assumptions for modeling framework

This chapter presents the Appendix to the framework introduction and analyses in Chapter 3, mainly including the data assumptions for the framework and the testbed. The setups for the testbed in Israel and the corresponding energy system flows between sectors are presented in this section. The assigned technological input and output sectors are presented in Table A.1.

To conclude the testbed setup, the assumed data are shortly described. A total of 560 single-family houses and 200 multi-family houses in Israel were assumed (Israel Central Bureau of Statistics, 2022). With about eleven households per multi-family house, this resulted in a total of 2800 households. Regarding decentralized technologies, a share of 30 % of renewable energy generation and 70 % gas-based generation was assumed (Ministry of Energy Department of Economics, 2018). In the following tables, the assumed maximum values (i.e., maximum power and maximum flows), as well as the conversion factors and costs, are summarised for each sector.

The assumptions for the emissions associated to the considered technologies are summarised in Table A.7.

Table A.1.: Input and output sector allocation to conversion technologies

Tech	Elec	Heat	Waste	Water	Gas
PV Generation	Out	/	/	/	/
Desalination	In	/	/	Out	/
Heat pump	In	Out	/	/	/
Hot Water	/	In/Out	/	In	/
Waste Comb.	Out	Out	In	/	/
Waste Biogas	/	/	In	/	Out
Gas CHP	Out	Out	/	/	In
Gas Boiler	/	Out	/	/	In
Blockheat	/	Out	/	/	In
Sewage Treat.	In	Out	/	In/Out	/
Sludge Comb.	Out	Out	/	In	/
Sludge Biogas	/	/	/	In	Out

Table A.2.: Framework electricity assumptions

Tech.	**Limit**	**Conversion**	**Costs**	**Comm.**
Elec. grid	80 MW	/	15 ct/kWh	11 kW per household, (Global Petrol Price, 2021b)
PV	1.73 MW	Standard profile	/	Half of households with PV
Heat pump	12.6 MW	COP time-series	0.15 ct/kWh	(IEA Heat Pump Centre, 2011; Nie et al., 2017)
Battery	0.285 MW	η of 0.95	0.3 ct/kWh	6 % of households, (Mongird et al., 2020)
Desalination	150 m^3	3 kWh/m^3 elec.	44 ct/m^3	(Schiermeier, 2014; Ghaffour et al., 2013)
Demand	/	3400 kWh	/	(Damari and Kissinger, 2018)

Table A.3.: Framework heat assumptions

Tech.	Limit	Conversion	Costs	Comm.
Boiler	33 MW	η of 0.95, water of 17 l/kWh	/	(Paschotta, 2021)
Heat storage	473 m^3	η of 0.8	0.05 ct/kWh	(Zablocki, 2019; Ouden et al., 2017)
Demand	/	35 GWh	/	(Qadi et al., 2018)

Table A.4.: Framework waste assumptions

Tech.	Limit	Conversion	Costs	Comm.
Storage	1343 m^3	/	/	Disposal periods
Stock	51 580 m^3	/	/	No disposal periods
Accruing	/	612 kg/year	/	(Ministry of Environmental Protection, 2019)
Disposal	/	1343 m^3	0.23 ct/kg	(Scott and Watson, 2006)
Combustion	75 MW	η_{el} of 0.35, η_{th} of 0.4	0.4 ct/kWh	(Kleppmann, 2014)

Table A.5.: Framework water assumptions

Tech.	**Limit**	**Conversion**	**Costs**	**Comm.**
Demand	/	758 520 m^3	/	(Israel Water Authority, 2011)
Storage	5988 m^3	/	1 ct/m^3	Basic assumptions
Sewage treatment	/	η_{water} of 0.95, η_{el} of 0.5 kWh/m^3	4 ct/m^3	(Ayoub et al., 2016; Huber Technology Waste Water Solutions, 2021)
Sewage sludge	/	9.2 kg/m^3	/	Based on sludge parameters
Sewage heat	/	3.5 kWh/m^3	/	(Cecconet et al., 2020)
Sludge combustion	2.2 MW	η_{el} of 0.35, η_{th} of 0.4	6 ct/kWh	Same as waste combustion
Sludge disposal	/	/	23 ct/kg	Same as waste

Table A.6.: Framework gas assumptions

Tech.	Limit	Conversion	Costs	Comm.
Demand	/	5112 MWh	/	(Worldometer, 2015)
Grid	1000 MW	/	/	(Global Petrol Price, 2021a)
Blockheat	6.4 MW	Efficiency 0.44	0.3 ct/kWh	(Zhang, 2020; Danish Energy Agency, 2016)
Boiler	31.5 MW	Efficiency 0.95	0.1 ct/kWh	Like waste combustion (higher efficiency)
CHP	31.5 MW	η_{el} of 0.35, η_{th} of 0.4	0.1 ct/kWh	Like waste combustion, (ESC Energy Solutions Center, 2021)
Anaerobic digestion	Waste: 75 MW Sludge: 2.2 MW	0.5 kg_{gas}/kg	7 ct/kg	(Verstraete et al., 2009)

Table A.7.: Framework emission assumptions

Technology	**Emissions**	**Comment**
Elec. grid	0.6 kg/kWh	(Lev-On et al., 2017)
Gas grid	0.02 kg/kWh	(Köppel et al., 2018)
Gas boiler	0.201 kg/kWh	(Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2021)
Blockheat	0.201 kg/kWh	(Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2021)
CHP	0.201 kg/kWh	(Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2021)
Waste combustion	$1.1\,kg/kg_{waste}$	(IEA Bioenergy, 2003)
Waste disposal	$0.382\,kg/kg_{waste}$	(Ritchie and Smith, 2009)
Sewage treatment	$0.3\,kg/m^3$	(Campos et al., 2016)
Sludge combustion	$50\,kg/m^3$	(Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2021)
Sludge disposal	$1456\,kg/m^3$	(Chen and Kuo, 2016)

B. LSC assumptions and modeling particularities

This chapter extends Chapter 4 to consumer and cost assumptions, presented in Section B.1. Furthermore, Section B.2 shows the detailed methodology of LSC services, including the carpool, washing machine, exhaust heat provision and water sale.

B.1. Consumer and cost assumptions

Basic assumptions on consumer configuration, technology costs and defined tariffs are presented in this section. Table B.1 presents the basic technology assumptions for consumers in the LSC. These assumptions are added to the optimization model as input parameters. Consumers' energy and resource demands must be given as time series input parameters to the model. The premises, which are based on the household size within the GeWoZu LSC are presented in Table B.2.

Aside from consumer assumptions, technology assumptions were made. Technologies are charged their operational costs. Predefined values of the RUTIS model based on literature research (based on Section A) were assumed for these costs. In the model extension, different tariff assumptions were made which are presented in the Tables B.3 to B.6 for all considered sectors in the case study. As emissions are considered, assumptions for CO2 emissions must be made which are presented in Table B.7. Grid emission factors are inconclusive because they vary over time. Basic values from Landesamt für Umwelt Brandenburg (2018) are assumed for the model analyses.

Table B.1.: GeWoZu consumer assumptions

Consumer	**Number people**	**PV in kWp**	**Battery in kWh**	**Heat pump in kW**	**Cooler in kW**	**Thermal storage in l**
1	4	2	5	7	7	300
2	4	5	/	/	/	/
3	4	/	/	/	/	/
4	4	/	/	/	/	/
5	3	2	/	/	/	/
6	3	/	/	/	/	/
7	3	2	/	/	/	/
8	2	/	5	7	7	/
9	2	/	/	/	/	/
10	2	3	/	7	7	300
11	1	/	/	/	/	/
12	1	/	/	/	/	300
LSC	/	20	25	30	30	1500

Table B.2.: GeWoZu demand assumptions

Nr. pers.	**1**	**2**	**3**	**4**	**Source**
Elec in kWh	2300	3000	3500	4000	(Weißbach, 2022)
Heat in kWh	2313	3278	4240	5205	(Rosenkranz, 2020)
Cooling in kWh	155	220	284	350	(Vogel, 2018)
Waste in kg	450	900	1350	1800	(Statistisches Bundesamt, 2022)
Water in m^3	42.5	85	127.5	170	(Jedamzik, 2022)

Table B.3.: LSC Electricity tariff assumptions

Parameter	**Identifier**	**Value**
Energy costs	$\Pi^{\text{LSC2elec,energy}}_{Elec,t}$	13 ct/kWh
Grid costs	$\Pi^{\text{grid}}_{Elec,t}$	6.2 ct/kWh
Fiscal charge	$\Pi^{\text{surcharge}}_{Elec,t}$	1.8 ct/kWh
Feed-in tariff	$\Pi^{\text{feedin}}_{Elec,t}$	7 ct/kWh
LSC tariff	$\Pi^{\text{LSC2elec,energy}}_{Elec,t}$	10 ct/kWh
Power price	$\Pi^{\text{power}}_{Elec}$	35 €/kW

Table B.4.: LSC heating and cooling tariff assumptions

Parameter	**Identifier**	**Value**
Heat energy costs	$\Pi^{\text{energy}}_{Heat,t}$	4.0 ct/kWh
Heat grid costs	$\Pi^{\text{grid}}_{Heat,t}$	4.6 ct/kWh
LSC heat tariff	$\Pi^{\text{LSC2energy,energy}}_{Heat,t}$	3.5 ct/kWh
Cooling energy costs	$\Pi^{\text{energy}}_{Cool,t}$	4.0 ct/kWh
Cooling grid costs	$\Pi^{\text{grid}}_{Cool,t}$	4.6 ct/kWh
LSC cooling tariff	$\Pi^{\text{LSC2energy,energy}}_{Cool,t}$	3.5 ct/kWh

Table B.5.: LSC water tariff assumptions

Parameter	Identifier	Value
Conventional pipeline tariff	$\Pi_{Water}^{\text{pipeline}}$	1.5 €/m^3
Water recovery purchase tariff	$\Pi_{Water}^{\text{recovery}}$	1.125 €/m^3
Water pool purchase and feed-in tariff	$\Pi_{Water}^{\text{waterpool}}$	0.75 €/m^3
Excess purchase tariff	$\Pi_{Water}^{\text{excess}}$	3 €/m^3

Table B.6.: LSC disposal cost assumptions

Parameter	Identifier	Value
Waste disposal costs	$\Pi_{Waste}^{\text{disposal}}$	23 ct/kg
Waste transport costs	$\Pi_{Waste}^{\text{transport}}$	0.09 ct/kg
Sludge disposal costs	$\Pi_{Sludge}^{\text{disposal}}$	414 €/m^3
Sludge transport costs	$\Pi_{Sludge}^{\text{transport}}$	0.09 ct/m^3

Table B.7.: Emission assumptions

Technology	**CO_2 Emissions**	**Comment**
Elec. grid	0.209 kg/kWh	(Landesamt für Umwelt Brandenburg, 2018)
Waste combustion	$1.1\,kg/kg_{waste}$	(IEA Bioenergy, 2003)
Waste disposal	$0.382\,kg/kg_{waste}$	(Ritchie and Smith, 2009)
Sewage treatment	$0.3\,kg/m^3$	(Campos et al., 2016)
Sludge combustion	$50\,kg/m^3$	(Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2021)
Waste and sludge transport	0.125 kg/km	(Schodl, 2019)
Waste disposal	$0.382\,kg/kg_{waste}$	(Ritchie and Smith, 2009)

B.2. Technology modeling

Several services were introduced in Section 4.1.4. The method and mathematical equations are described in this section.

Carpool

A set of electric vehicles in the carpool is predefined, representing all available vehicles in the LSC. A combination of cars cannot cover the transport demand. Thus, only one vehicle can be used to cover the transport demand of a consumer per timestep. This approach requires the use of binary variables, where the model is transformed into a MILP. The binary transport demand coverage is presented in Equation B.2. The distance covered by a vehicle is represented by $s_{v,t}$.

$$\mathcal{V} = Vehicle_1, Vehicle_2, ..., Vehicle_n \tag{B.1}$$

$$D_{transport_i} = \sum_{v \in \mathcal{V}} bin_{i,v,t} \cdot s_{v,t} \quad \forall i \in \mathcal{C} \tag{B.2}$$

Binary sums are required to guarantee that the demand can be covered by only one vehicle (Equation B.3) and that a car cannot be used for multiple demands (Equation B.4).

$$\sum_{v \in \mathcal{V}} bin_{i,v,t} \leq 1 \quad \forall i \in \mathcal{C} \tag{B.3}$$

$$\sum_{i \in \mathcal{C}} bin_{i,v,t} \leq 1 \quad \forall v \in \mathcal{V} \tag{B.4}$$

As final vehicle constraints, charging and driving need to be blocked at the same time for each vehicle. The consumed energy is determined by vehicle energy consumption $K_v^{\text{energydemand,drive}}$.

$$q_{v,t}^{\text{drive}} \leq bin_{i,v,t} \cdot s_{v,t} \cdot K_v^{\text{energydemand,drive}} \quad \forall v \in \mathcal{V} \tag{B.5}$$

$$q_{v,t}^{\text{charge}} \leq (1 - bin_{i,v,t}) \cdot P_{max}^{\text{charge}} \quad \forall v \in \mathcal{V} \tag{B.6}$$

Washing machine

The GeWoZu has a modern washing machine where the water is heated electrically within the washing machine as the first option. The second option for water is to be sourced directly from hot water access. Heat from the washing machine sewage can be recovered. Electricity, heat and water are the required inputs for the washing machine while recovered heat and washing service are the outputs.

The energy demand of the washing machine is set together with a fixed electricity demand $Q_t^{\text{wash,fix}}$ for motor and sensor operation (0.15 kWh/cycle), and from electric $q_{Elec,t}^{\text{washheat}}$ or thermal heating $q_{Heat,t}^{\text{washheat}}$ of water. The demand per washing cycle is presented in Equation B.7. The optimizer decides whether the water should be electrically or thermally heated.

$$q_t^{\text{wash,tot}} = (Q_t^{\text{wash,fix}} + q_{Elec,t}^{\text{washheat}} + q_{Heat,t}^{\text{washheat}}) \tag{B.7}$$

The volume of the water in the washing machine must be heated. The required energy depends on the washing cycle temperature difference ΔT, thermal water capacity c_v^{water} and the density of water ρ^{water}. Washing temperature time series are assigned randomly. Electric heating in the washing machine is considered with the efficiency of the internal heating system η^{washheat}. The assumptions lead to Equation B.8.

$$\rho^{\text{water}} \cdot V^{\text{wash}} \cdot c_v^{\text{water}} \cdot \Delta T = \eta^{\text{washheat}} \cdot q_{Elec,t}^{\text{washheat}} + q_{Heat,t}^{\text{washheat}} \tag{B.8}$$

The recovered energy depends on the temperature difference, the share of sewage in water, the heated water volume, and the factor $K^{\text{wash,recovery}}$.

$$q_t^{\text{wash,recovery}} = Share^{\text{sewage}} \cdot V^{\text{wash}} \cdot K^{\text{wash,recovery}} \cdot \Delta T \tag{B.9}$$

Exhaust heat provision

External service providers such as industries can sell exhaust process heat to the LSC at predefined prices. Access to district heat grids is required and is assumed to be possible in the considered scenarios with exhaust heat provision. The LSC operator purchases the exhaust heat. Costs are dependent on the predefined price in the agreement $\Pi_{Heat}^{\text{industryexhaust}}$ and the grid costs Π_{Heat}^{grid}.

$$c_{LSC,Heat,t}^{\text{industryexhaust}} = q_t^{\text{industryexhaust}} \cdot (\Pi_{Heat}^{\text{industryexhaust}} + \Pi_{Heat}^{\text{grid}}) \tag{B.10}$$

The purchased heat is limited by the processing power that provides exhaust heat.

$$q_t^{\text{industryexhaust}} \leq P_{max}^{\text{industryexhaust}} \cdot \Delta t \tag{B.11}$$

On balance, emissions are assigned directly to the process rather than to exhaust heat. Therefore, no emissions are assumed for procuring exhaust heat. Service provisions are strongly dependent on the agreement with the LSC. Contracts that require a minimum purchased heat amount of 3 kWh per time step are investigated in separate analyses, where the provided heat is limited to 6 kWh per time step. The relation is implemented according to the constraint in Equation B.12.

$$3\,\text{kWh} \leq q_t^{\text{industryexhaust}} \leq 6\,\text{kWh} \tag{B.12}$$

Water sale

Water sale is implemented to ensure that a certain portion of the sewage, referred to as greywater (Maldet et al., 2022b), can be sold to external consumers for irrigation or other purposes. The amount of sold sewage is limited to the share of greywater in sewage.

$$v_{LSC,t}^{\text{greywater,sold}} \leq Share^{\text{greywater}} \cdot v_{LSC,t}^{\text{sewage}} \tag{B.13}$$

The balance rule for sewage is changed, because not all sewage is treated. This situation results in competition in savings from sewage energy and resource recovery and sale of greywater.

$$v_{\text{LSC,t}}^{\text{sewage}} = v_{LSC,t}^{\text{greywater,sold}} + v_{LSC,t}^{\text{greywater,treated}} \tag{B.14}$$

For the greywater sale, predefined prices are assumed according to the conventional pipeline purchase price $\Pi_{Water}^{\text{pipeline}}$. These are multiplied by different price factors $F^{\text{watermarket}}$, and different factor assumptions are subjected to a sensitivity analysis. Revenues depend on the price and the amount of sold greywater.

$$rev_{LSC,t}^{\text{greywater,sold}} = v_{LSC,t}^{\text{greywater,sold}} \cdot F^{\text{watermarket}} \cdot \Pi_{Water}^{\text{pipeline}} \tag{B.15}$$

C. LSM assumptions and sectoral model equations

This chapter shows the Appendix to Chapter 5. Section C.1 presents the balance rules for the sectors, that are considered in the LSM in Chapter 5. Additionally, Section C.2 presents the fundamental assumptions for the LSM analyses.

C.1. Balance rule representation

In this section, the balance rules described in Section 5.1 are graphically presented. Furthermore, additional model equations required for understanding the technical functionalities are emphasized.

Waste sector

Waste is set together of municipal waste and sewage sludge. Emerging waste is assumed as time-constant input time series. Basic assumptions consider the incineration of both resources. Electricity and heat can be recovered. However, it can be assumed that not all energy can be reused in the municipality. This results in the following waste incineration equations.

$$q_{comb,t}^{\mathrm{elec}} = \eta_{comb}^{\mathrm{elec}} \cdot m_{comb,t}^{\mathrm{waste}} \cdot share_{comb}^{\mathrm{usable}} \tag{C.1}$$

$$q^{heat}_{comb,t} = \eta^{heat}_{comb} \cdot m^{waste}_{comb,t} \cdot share^{usable}_{comb} \tag{C.2}$$

$$em_{comb,t} = F^{CO2}_{comb} \cdot m^{waste}_{comb,t} \cdot share^{nonbiogene}_{comb} \tag{C.3}$$

Extensions of waste portfolios consider anaerobic digestion for biogas generation, as presented in Figure C.1.

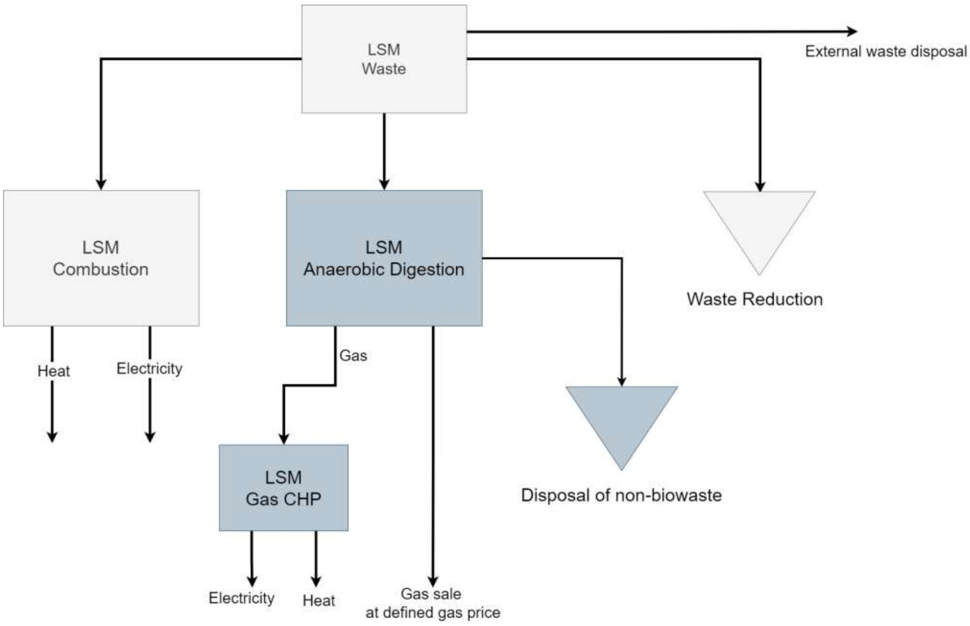

Figure C.1.: Waste treatment options

Generated biogas presented in Equation C.4 can be incinerated or sold externally.

$$q^{gas}_{wasteAD,t} = m^{waste}_{wasteAD,t} \cdot \eta_{wasteAD} \cdot H^{waste}_{S} \cdot share^{biodegradable} \tag{C.4}$$

Incinerated biogas is determined by investment decisions in gas CHP plants. Relations are similar to Equations C.1 and C.2, with the significant difference that for biogas incineration, no direct emissions are assumed. However, only biodegradable waste can be digested. The share of non-biodegradable waste must be thermally treated, resulting in the same emissions as waste incineration. Apart from extensions to zero-emission anaerobic digestion with combined recycling of non-biodegradable waste, the same emissions are assumed for both treatment options.

Waste can be transported between different LSM positions by waste trucks at defined distance-dependent costs and emissions to prevent treatment at multiple sites. However, to avoid circular flows of waste, input and output for waste transport in the same time steps are prohibited by the introduction of binary-blocking constraints.

$$m_{m,n,t}^{\text{wastetrans,out}} \leq bin_{m,n,t}^{\text{wastetrans,out}} \cdot M_{trans}^{\text{waste,max}} \quad \forall m,n \in \mathcal{M}, m \neq n \tag{C.5}$$

$$m_{m,n,t}^{\text{wastetrans,in}} \leq (1 - bin_{m,n,t}^{\text{wastetrans,out}}) \cdot M_{trans}^{\text{waste,max}} \quad \forall m,n \in \mathcal{M}, m \neq n \tag{C.6}$$

Water and sewage sector

Water and sewage are implemented using a circular economy approach. Sewage from LSCs is jointly treated by the LSM, whereas recovered water can be sold by the LSM to the LSCs at distance dependent prices. Sludge as a by-product is assigned to the waste sector. Similar to waste, sewage can be transmitted between different positions to prevent multiple sewage treatment plant installations. The major difference is that for sewage transmission, no costs and emissions are assumed due to the pipeline-based transmission system. Moreover, the implementation of greywater systems is investigated as presented in Section 5.1.3. The setup for the water and sewage circular economy implementation is presented in Figure C.2.

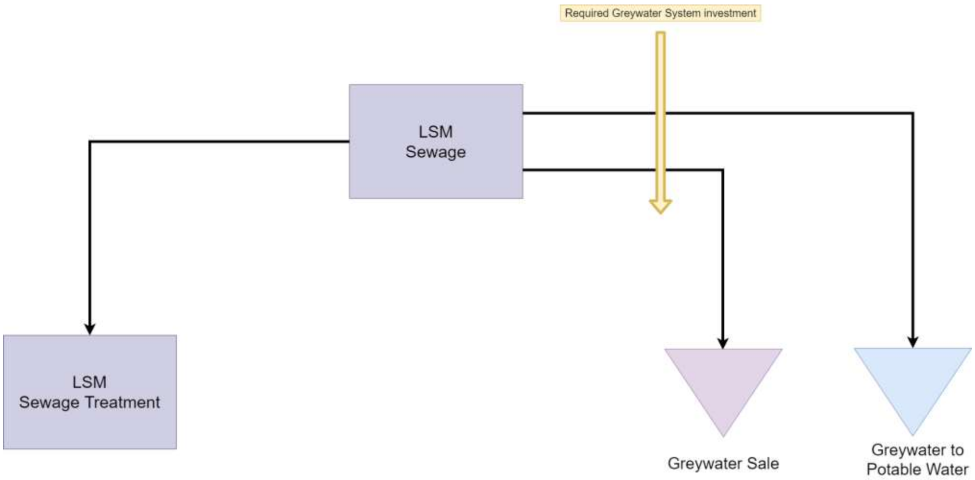

Figure C.2.: Sewage treatment options

Electricity sector

Figure C.3 presents electricity inputs and outputs of the LSCs and LSM.

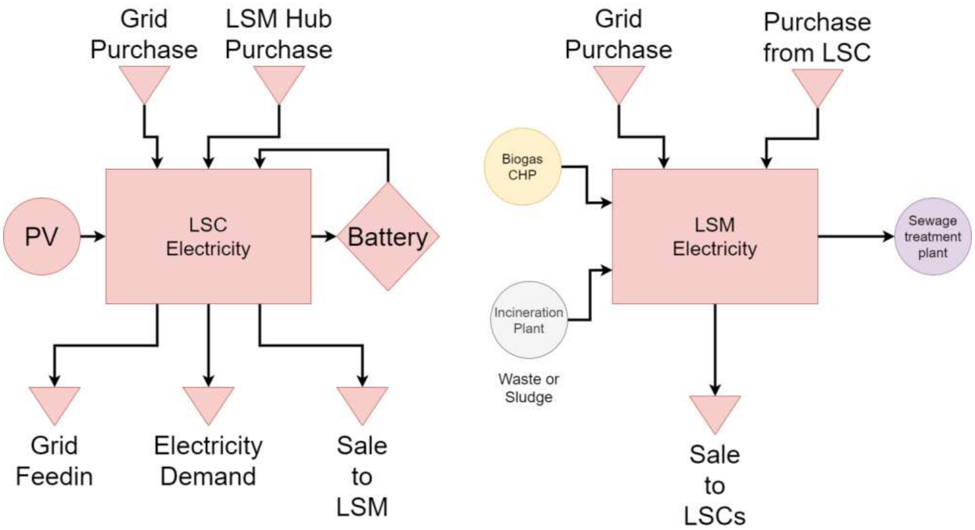

Figure C.3.: Electricity inputs and outputs

The goal is to cover the given electricity demand for all consumers. Installed

PV systems and market procurement from the LSM can provide LSC electricity. The remaining electricity can be procured from the public electricity grid. Excess electricity can be sold on the LSM market or fed back into the electricity grid at pre-defined prices. Moreover, battery investment is included in the analyses. LSM electricity can be procured over the LSM market and from the electricity grid. Recovered electricity from waste or biogas incineration is assigned to the LSM. The LSM must provide the required electricity for sewage treatment. The remaining electricity can be sold to the LSCs at distance-dependent efficiencies and grid prices. To understand the setting of efficiencies and prices, Figure C.4 presents the electricity grid setup of the LSM.

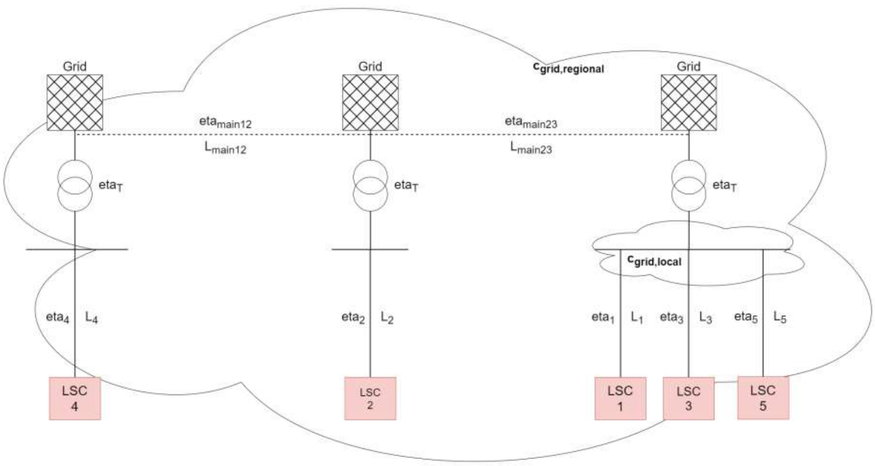

Figure C.4.: LSM electricity grid

Transformer efficiencies and efficiencies depending on the line length are assumed. Grid tariffs are set based on grid level, differing between local and regional grid tariffs.

Heat sector

Figure C.5 presents the balance rules in the heat sector.

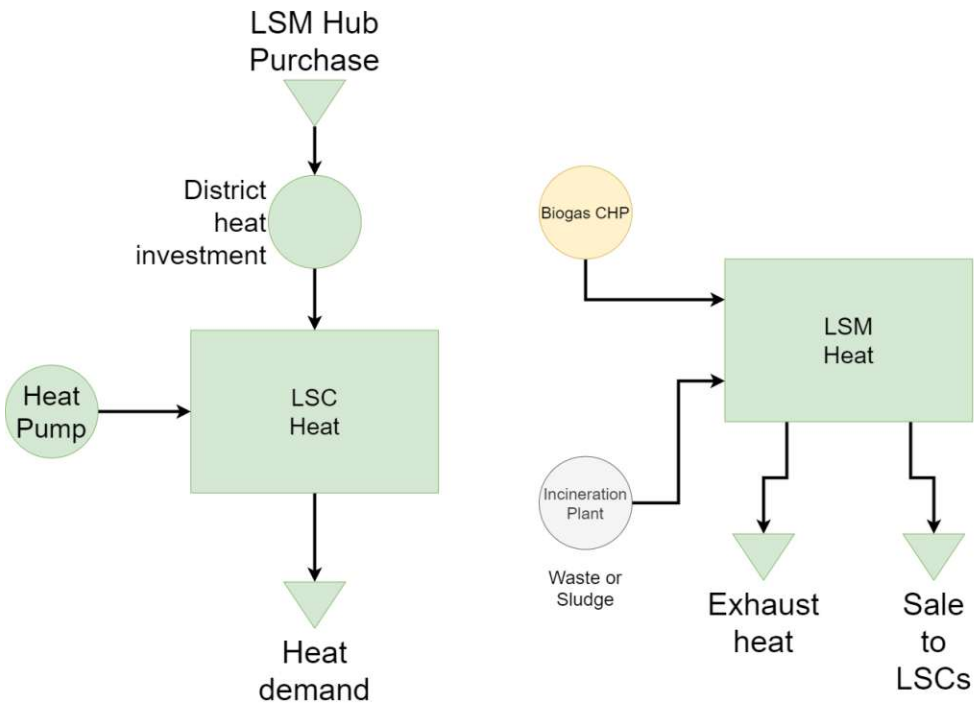

Figure C.5.: Heat inputs and outputs

Installed heat pumps can generate LSC heat to cover the pre-defined heat demand. Moreover, investment decisions in district heat connections are performed. Heat can be procured from local LSM markets if investment in district heat connection is performed. The source of the procured heat can be either waste or biogas incineration, as it can be seen in the balance rule of the LSM. Procurement costs are dependent on grid length, similar to the electricity sector, without the assumption on the difference in distance-dependent grid tariffs for heat.

C.2. Consumer, cost and technology assumptions

The different assumptions considered for the input parameters of the consumers are presented in this section. The municipality provided data for the public facilities and resident statistics. Demand and technology assumptions

Table C.1.: Municipality configuration

LSC	**Electricity in** MWh	**Heat in** MWh	**Water in** m^3	**Waste in** t
1	359	2200	17112	167
2	441	2680	20838	204
3	402	2467	19182	188
4	328	2005	15594	153
5	166	585	1669	136

are taken based on household statistics. For the demand profiles, the aggregations of residents in LCSs presented in Table 5.1 are considered. The percentual share of household sizes is assumed according to Statistik Austria, 2022. Electricity consumption per consumer is considered based on Gonzalez, 2022, whereas heat consumption relies on the assumptions of Kloth, 2022a. Annual water consumption is assumed based on Jedamzik, 2022, while accruing waste input comes from statistics of the considered municipality. This leads to the demand assumptions in Table C.1.

Technology data are assumed based on the household size. PV generation profiles are considered based on Österreichs Energie, 2020 while COP profiles of heat pumps are taken based on Nie et al., 2017. The maximum technology capacity assumptions for each LSC are summarized in Table C.2.

Existing waste storage capacities are assumed with 1/12 of the accruing waste, with potential expansion of 141 t. Maximum resource treatment and gas CHP capacities for investment decisions are assumed to be sufficiently high to guarantee model feasibility. The same applies to the input parameter of maximum waste transport mass. Waste transport distance varies between 0.6 km and 2.4 km based on geographical distances in the municipality, with LSC3 having the shortest distance to other LSCs in sum. Transport emissions are directly related to transport distances. For electricity lines, 10 % losses per 1000 km are assumed, according to Siemens, 2017. Additionally, transformer losses of 1 % are taken based on Belefic, 2022. For heat procure-

Table C.2.: Municipality technology assumptions

LSC	**PV in** kWp	**Battery in** kWh	**Heat pump in** kW	**District heat in** kW
1	1630	1630	1141	1141
2	2162	2300	1610	1610
3	2000	2000	1400	1400
4	1010	1370	1370	1370
5	412	190	400	400

ment, losses of 1 % per km are assumed, according to Kavvadias and Quoilin, 2018.

Tariffs for external procurement and LSM market operation are summarized in Table C.3. Potential electricity prices for 2040 are assumed based on Ministère de l'environnement, de l'énergie et de la mer (2017).

Technology operational costs are considered to have the same values as presented in Section A. Finally, Tables C.4 and C.5 present the taken investment costs. Amortization periods are assumed based on Bundesministerium der Finanzen and Juris Das Rechtsportal, 2023.

Table C.3.: Municipality tariff assumptions

Tariff	**Value**
Electricity purchase	29.7 cent/kWh
Electricity purchase 2040	12.83 cent/kWh
Electricity feedin	7 cent/kWh
Electricity LSM sale	14.35 cent/kWh
Electricity LSM purchase local	18.82 cent/kWh
Electricity LSM purchase regional	20.61 cent/kWh
LSM heat purchase	3 cent/kWh
Water pipeline purchase	1.5 €/m^3
Water LSM purchase	1.35 €/m^3
Water LSM purchase at same position	1 €/m^3
Waste transport costs	0.23 €/kg
Waste disposal costs	1.5 €/kg
CO_2 price	30 €/t
Gas price low	0.79 cent/kWh
Gas price high	23.7 cent/kWh

Table C.4.: Municipality investment cost assumptions for energy technologies

Technology	**Fixed costs**	**Variable costs**	**Amortization period in years**	**Source**
PV	3500 €	1300 €/kWp	20	(Daniel and Sattlberger, 2022)
Battery	900 €	1000 €/kWh	10	(Kloth, 2022b)
Heat pump	500 €	945 €/kWh	8	(IEA, 2022, Tsoukanta, 2022)
District heat connection	350 €	500 €/kW	20	(Bio fernwärme, 2023)

Table C.5.: Municipality investment cost assumptions for resource technologies

Tech.	**Fixed costs**	**Variable costs**	**Amortization period in years**	**Src.**
Waste combustion	150 000 €	5200 €/kg	10	(Convex, 2022)
Waste storage	6200 €	10 €/kg	10	(Heimhelden.de, 2023, Kostencheck, 2022)
Sewage treatment plant	353 000 €	70 000 €/m^3	20	(Samco, 2016, Johnson, 2022)
Anaerobic digestion	150 000 €	4000 €/kW	10	(Grebe, 2017)
Gas CHP	-	1970 €/kW	16	(Oluleye and Hawkes, 2020)
Greywater system	6500 €/unit	-	15	(Anders bauen und wohnen, 2023)

D. SDG indicator model assumptions and extended case study results

This final chapter of the Appendix presents the data assumptions of Chapter 6 in Section D.1. Furthermore, Section D.2 presents additional results to Chapter 6, including the results of the policy paths in the community and municipality.

D.1. Data assumptions

This section provides an overview of the assumptions in the case studies presented in Sections 6.2.1 and 6.2.2.

The community and municipality's business-as-usual (BaU) values are determined by separate optimization analyses without sustainable operations and technology investment. BaU results for the community are 23.77k€ as total costs and 19.8 t_{CO2} for the emissions. For the municipality, BaU results indicate 2438k€ and 1611 t_{CO2}.

Table D.1 presents the tariff assumptions for both, the community and municipality.

Table D.2 presents the technology investment cost assumptions. Amortization periods are assumed based on Bundesministerium der Finanzen and Juris Das Rechtsportal (2023). Operational costs are assumed as in Maldet et al., 2022b. Table D.3 presents the assumed maximum technologies in the

Table D.1.: Tariff assumptions

Tariff	**Value**
Electricity purchase	29.7 cent/kWh
Electricity feedin	7 cent/kWh
District heat purchase	7.6 cent/kWh
Water pipeline purchase	1.5 €/m^3
Recovered water purchase	1.35 €/m^3
Waste disposal costs	0.23 €/kg
Waste recycling costs IKB, 2023	0.38 €/kg
Sewage disposal costs	2.28 €/m^3
CO_2 price	30 €/t

community and municipality. Technologies were considered based on the case study sites' provided community and municipality data.

Table D.4 gives an overview of the energy and resource demands. Demands were assumed based on household sizes, whereas for the municipality, demands of public buildings were provided by the investigated municipality. Moreover, the total accruing waste amount was provided for the whole municipality.

Finally, Table D.5 presents the emission assumptions. Waste emissions are adapted, as only the nonbiogenic share of waste leads to emissions. However, sludge as a by-product from sewage treatment is also incinerated and counted as biogenic, leading to a higher total biogenic percentage and thus, to lower waste incineration emissions. Disposal and treatment of waste and sewage are assumed with the same emissions, as disposal leads to treatment beyond the system boundaries. Moreover, the share of renewable energy generation in the electricity grid of 80 % (Wien Energie, 2022) and in the district heating grid of 33 % (ENBW Fernwärme, 2020) must be considered.

Table D.2.: Investment cost assumptions with a WACC of 3 %

Technology	**Costs**	**Amortization period in years**	**Source**
PV	1300 €/kWp	20	Daniel and Sattlberger, 2022
Battery	1000 €/kWh	10	Kloth, 2022b
Heat pump	945 €/kWh	8	IEA, 2022, Tsoukanta, 2022
District heat connection	500 €/kW	20	Bio fernwärme, 2023
Waste combustion	5200 €/kg	10	Convex, 2022
Sewage treatment plant	70 000 €/m^3	20	Samco, 2016, Johnson, 2022
Greywater system	520 €/l -	15	Anders bauen und wohnen, 2023

Table D.3.: Technology capacity assumptions in the community and municipality

Technology	**Community**	**Municipality**
PV	30 kWp	7214 kWp
Battery	30 kWh	7214 kWh
Heat pump	30 kW_{therm}	5000 kW_{therm}
District heat connection	30 kW	5000 kW
Waste combustion	-	800 t/h
Sewage treatment plant	-	20 m^3/h
Greywater system	150 l	9125 l

Table D.4.: Annual energy and resource demands in community and municipality

Sector	**Community**	**Municipality**	**Sources**
Electricity	40.8 MWh	1696 MWh	Weißbach, 2022, Gonzalez, 2022
Heat	48 MWh	9937 MWh	Rosenkranz, 2020, Kloth, 2022a
Water	1405 m^3	74 197 m^3	Jedamzik, 2022
Waste	15 t	848 t	Statistisches Bundesamt, 2022

Table D.5.: Emission assumptions for technologies and actions

Technology	**Emissions**	**Source**
Electricity grid	0.209 kg_{CO2}/kWh	Landesamt für Umwelt Brandenburg, 2018
District heat	0.188 kg_{CO2}/kWh	ENBW Fernwärme, 2020
Sewage disposal	0.300 kg_{CO2}/m^3	Campos et al., 2016
Waste disposal	0.125 kg_{CO2}/kg	IEA Bioenergy, 2003
Sewage treatment	0.300 kg_{CO2}/m^3	Campos et al., 2016
Waste combustion	0.125 kg_{CO2}/kg	IEA Bioenergy, 2003

Table D.6.: Community technology installation impact of SDG Path 1

Sens. in %	PV in kWp	Battery in kWh	Heat pump in kW	District heat in kW	Grey water systems in l
0	30.00	3.65	3.93	13.86	0
5	30.00	3.65	3.93	13.86	8
45	30.00	3.65	3.93	13.86	150
50	30.00	3.65	4.69	13.10	150
70	30.00	3.95	14.47	3.32	150
90	29.86	3.98	14.21	3.58	150
100	30.00	4.00	14.97	2.80	150

D.2. Case study results

This section summarizes the detailed results of the community and municipality analyses for all paths according to Figure 6.2.

D.2.1. Community case study results

This section focuses on the results of the policy paths in the community.

The following tables present the sensitivity analysis for specific SDG target setting in the community, according to Path 1. Table D.6 illustrates the impact on technology installation and Table D.7 shows the effects on SDG contribution targets. Only the relevant sensitivities where SDG targets become active or reach their limit are presented.

Heat pumps and greywater systems are increasingly installed to reach the

Table D.7.: Community SDG contribution target impact SDG Path 1

Sens. in %	**SDG1**	**SDG6**	**SDG7**	**SDG12**	**SDG13**
0	21	0	73	0	42
5	20	5	73	5	42
45	-4	45	73	45	47
50	-5	45	75	50	50
70	-10	45	90	88	70
90	-11	45	90	90	70
100	-11	45	90	100	70

proposed SDG targets. District heating connection is decreased, whereas other technologies are only slightly affected. Emission reductions are limited because of the high dependency on the electricity grid, a significant source of emissions in the community. SDG1 becomes negative at targets of 45 %. Thus, the costs are higher than that in the BaU case, leading to non-cost-efficient operation. However, the reduction of water and waste (as additional sensitivity) can extend the SDG limits and keeps SDG1 at a higher level while reaching the same targets.

Table D.8 presents the impact of penalty incentive schemes on technology installation in the community and Table D.9 presents their implications on SDG contribution targets. CO_2 price extension considers prices of 0.15 €/kg_{CO2}. The exact values of the investment schemes are presented in Table 6.4.

Increased sewage disposal costs lead to greywater installation becoming an economically feasible option and thus to increased SDG6 contribution. Moreover, additional district heating costs lead to heat pumps becoming the dominant heat generation technology. Additional heat pump installation leads to improvement in SDG7 contribution. Increasing waste disposal costs lead to full waste recycling (as no limit was assumed), which leads to a maximum SDG12 target. High CO_2 prices increase SDG13. Such prices affect not only

Table D.8.: Community technology installation impact SDG Path 2

Policy action	PV in kWp	Battery in kWh	Heat pump in kW	District heat in kW	Grey water systems in l
Sewage disposal penalties	30	3.65	3.93	13.86	67
District heat penalties	30	3.65	10.50	7.31	0
Waste disposal penalties	30	3.65	3.93	13.86	0
CO_2 price extension	30	3.95	14.47	3.32	0
Penalty combination	30	3.68	11.22	6.57	67

SDG13 but also SDG7 and SDG12. However, all of the penalties lead to increased total costs and thus, to a decrease in SDG1. Incentive schemes that consider greywater further lead to negative SDG1 contributions and thus to higher costs than those in the BaU scenario. Therefore, a detailed analysis on the incentive costs (as performed in Table 6.4) is mandatory for penalty impact assessment.

Tables D.10 and D.11 present the investment subsidy incentive schemes and their impact on technology installation and SDG target achievement. CO_2 price extension considers prices of $0.15\,€/\mathrm{kg}_{\mathrm{CO2}}$.

Table D.9.: Community SDG contribution target impact of SDG Path 2

Policy action	SDG1 in %	SDG6 in %	SDG7 in %	SDG12 in %	SDG13 in %
Sewage disposal penalties	-29	29	73	0	43
District heat penalties	19	0	87	0	57
Waste disposal penalties	12	0	73	100	51
CO_2 price extension	-20	0	90	50	65
Penalty combination	-42	29	88	100	68

Investment subsidies lead to similar results as penalties. Therefore, investment subsidies can be an alternative approach to promote SDG contribution. SDG1 does not decrease, as the investment incentives are not directly provided by consumers. However, as it must be assumed that the funding agency provides the investment subsidies from tax revenues, investment incentives are also indirectly paid by consumers. Therefore, the comparison must be performed in terms of costs for incentive schemes.

A combination of penalties and investment subsidies also leads to similar results as those in Paths 2 and 3 in particular while keeping SDG1 at a higher level than that with penalties alone. Figure D.1 presents the results of a combined incentive scheme approach in the community.

All three policy paths in the community lead to similar results. However,

Table D.10.: Community technology installation impact of SDG Path 3

Policy action	PV in kWp	Battery in kWh	Heat pump in kW	District heat in kW	Grey water systems in l
Greywater investment subsidies	30	3.65	3.93	13.86	60
Heat pump investment subsidies	30	3.65	8.88	8.90	0
Waste recycling subsidies	30	3.65	3.93	13.86	0
CO_2 price extension	30	3.68	6.57	11.20	0
Subsidy combination	30	3.68	110.81	6.97	60

Table D.11.: Community SDG contribution target impact of SDG Path 3

Policy action	SDG1 in %	SDG6 in %	SDG7 in %	SDG12 in %	SDG13 in %
Greywater investment subsidies	22	28	73	0	42
Heat pump investment subsidies	23	0	85	0	55
Waste disposal penalties	22	0	73	100	51
CO_2 price extension	18	0	80	0	50
Subsidy combination	22	28	87	100	68

Path 1 requires strict policy setting, whereas Paths 2 and 3 require incentive scheme costs. Moreover, combining penalties and investment subsidies leads to the most efficient incentive scheme in the community.

D.2.2. Municipality case study results

This section focuses on the results of the policy paths in the municipality.

Tables D.12 and D.13 present the impact of the SDG target sensitivity analyses on technology installation and SDG contribution according to policy

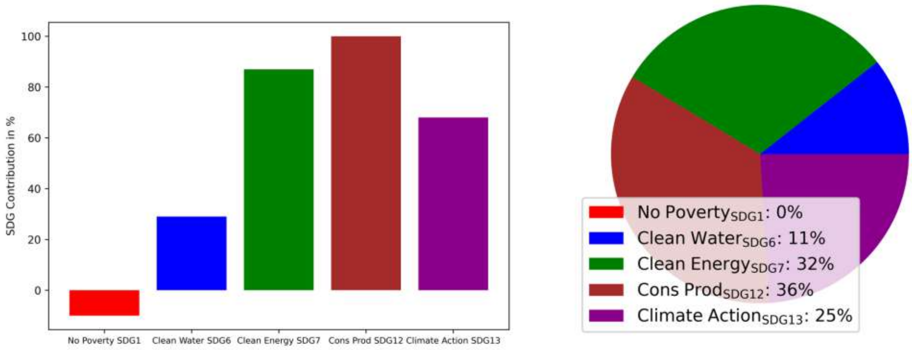

Figure D.1.: Combined incentive scheme for communities

Path 1. Table D.12 includes PV, battery (Bat), heat pump (HP), district heat (DH), greywater (GW), waste incineration (Inc.) and sewage treatment (Sew. treat) capacities.

As for the community, heat pump installation increases in favour of district heat installation. Moreover, PV installation decreases to prevent electricity excess feed-in electricity. Owing to the implemented waste incineration energy recovery, the amount of excess electricity in the system is already high without PV installation. Thus, additional PV installation leads to increased SDG7 contribution in the system. SDG6 can be achieved without greywater installation due to the implemented sewage treatment water recovery, which is the significant difference to the community analyses. With the implemented water reduction, the limit of SDG7 can be extended to 90 %.

The Tables D.14 and D.15 show the penalty (pen) incentive scheme impact of Path 2. Exact investment scheme values are presented in Table 6.5. Extended CO_2 prices are assumed at 3.1 €/kg_{CO2}.

As in the community, sewage treatment penalties increase greywater system installation. Moreover, more expensive district heat procurement costs promote heat pump establishment and waste combustion penalties encourage recycling. However, high CO_2 prices and greywater installation lead to

Table D.12.: Municipality technology installation impact SDG Path 1

Sens. in %	PV in kWp	Bat in kWh	HP in kW	DH in kW	GW in l	Inc. in kW	Sew. treat in l
0	7214	634	1545	2137	0	579	8025
5	7214	638	1550	2132	0	550	8025
50	7214	754	1588	2094	420	283	7600
60	7195	817	1877	1805	2110	241	5900
70	5098	790	1934	1748	3800	239	4220
85	3172	779	2538	1144	3800	156	4220
90	3993	2663	3311	371	4012	118	4012
95	4005	6459	3444	238	4012	66	4012
100	4044	6639	3457	225	4012	0	4012

Table D.13.: Municipality SDG contribution target impact SDG Path 1

Sens. in %	SDG1 in %	SDG6 in %	SDG7 in %	SDG12 in %	SDG13 in %
0	35	48	54	0	71
5	33	48	54	5	71
50	18	50	56	50	74
60	13	60	60	60	80
70	6	70	70	70	81
85	-4	70	85	85	85
90	-29	70	90	90	90
95	-65	70	95	95	90
100	-68	70	95	100	90

Table D.14.: Municipality technology installation impact of SDG Path 2

Policy action	PV in kWp	Bat. in kWh	HP in kW	DH in kW	GW in l	Inc. in kW	Sew. treat in l
Sew. treat pen	7214	677	1570	2112	4010	454	4012
DH pen.	7214	749	2455	1228	0	579	8025
Inc. pen.	7214	807	1537	2145	0	0	8025
CO_2 price ext.	7214	1189	2952	730	4012	1489	4012
Pen. combi.	7214	880	2635	7047	4012	0	4012

Table D.15.: Municipal SDG contribution target impact of SDG Path 2

Policy action	SDG1 in %	SDG6 in %	SDG7 in %	SDG12 in %	SDG13
Sew. treat pen.	12	71	55	0	73
DH pen.	31	48	61	0	83
Inc. pen.	1	48	57	100	74
CO_2 price ext.	-29	71	66	21	92
Pen. combi.	-20	71	66	100	89

Table D.16.: Municipality technology installation impact of SDG Path 3

Policy action	PV in kWp	Bat. in kWh	HP in kW	DH in kW	GW in l	Inc. in kW	Sewage treat in l
GW inv. sub.	7214	677	1570	2112	4012	454	4012
HP inv. sub.	7214	727	2211	1471	0	579	8025
Rec. sub.	7214	807	1537	2145	0	0	8025
CO_2 price ext.	7214	744	1911	1771	0	579	8025
Sub. combi.	7214	880	2583	1099	4012	0	4012

higher costs than in the BaU scenario. Therefore, similar to the community, detailed incentive scheme costs are mandatory to analyze. Finally, Table D.16 shows the impact of municipal investment subsidy (inv. sub.) incentive schemes on technology installation. Table D.17 presents the impact on SDG target contributions. Both tables show the results according to municipal policy Path 3. Extended CO_2 prices are assumed at 0.1 €/kg_{CO2}.

The proposed investment subsidies lead to similar results as those of penalties, with the difference that the subsidies are indirectly covered by municipal consumers by tax payments. Therefore, SDG1 is not the only indicator to be considered. Incentive scheme costs are mandatory to be considered as well. Figure D.2 presents the SDG contributions of a combined incentive scheme. Similar to the community, a combination of penalty and investment subsidy incentive schemes, particularly a combination of Paths 2 and 3, leads to the lowest costs and is, therefore, the most efficient incentive scheme.

Table D.17.: Municipal SDG contribution target impact of SDG Path 3

Policy action	SDG1	SDG6	SDG7	SDG12	SDG13
GW inv. sub.	71	55	0	73	36
HP inv. sub	48	60	0	81	42
Rec. sub.	48	57	100	74	36
CO_2 price ext.	48	58	0	77	31
Sub. combi.	71	65	100	89	41

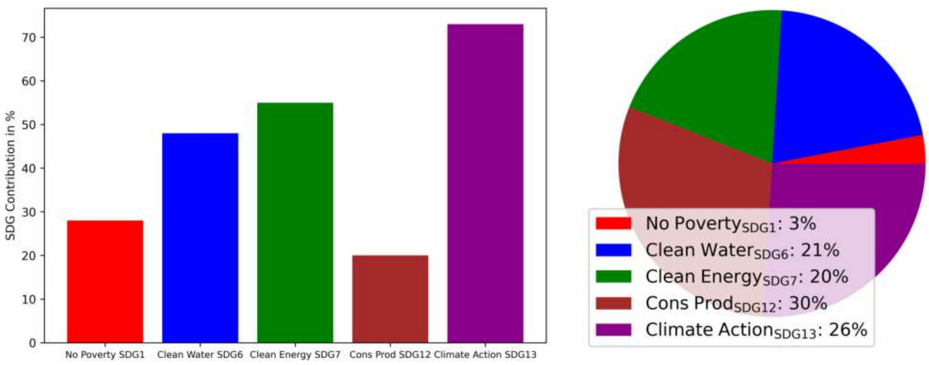

Figure D.2.: Combined incentive scheme for municipality