Cleaner Energy Systems 7 (2024) 100106

Contents lists available at ScienceDirect

Cleaner Energy Systems

journal homepage: www.elsevier.com/locate/cles

Local sustainable communities: Sector coupling and community optimization in decentralized energy systems

Matthias Maldet *, Daniel Schwabeneder, Georg Lettner, Christoph Loschan, Carlo Corinaldesi, Hans Auer

Institute of Energy Systems and Electrical Drives, Energy Economics Group (EEG), Technical University of Vienna, Vienna, Austria

ARTICLE INFO

Keywords:
Local sustainable community
Decentralization
Resource utilization
Sustainable Development Goals
Business models

ABSTRACT

Achieving local sustainable development often depends on consumers' incentives to efficiently utilize energy and resources. In this paper, Local sustainable communities (LSC) are introduced as a combination of sustainable communities and local energy communities to promote local energy and resource utilization. Business models on technology and service provision and those on promoting sustainable resource utilization are developed, which are then applied to a community in Austria. A modeling framework on sector coupling in community operations, that also considers resource utilization is developed to assess the impact of the business models. LSC business models promote participation and sustainable operation in an LSC as 31% of electricity and 34% of heat can be covered by LSC purchase. The implementation of energy recovery business models and the availability of sufficient decentralized technologies have the greatest impact on LSC operations, reducing external electricity grid coverage to 58%. The consideration of resource business models can positively contribute to a local resource utilization efficiency, reducing the water pipeline coverage by 43%. The introduction of an LSC has a positive impact on the United Nations Sustainable Development Goals and can therefore efficiently contribute to the development of a cleaner energy system.

1. Introduction

The global CO_2 emissions from energy generation-related and industrial processes are steadily increasing (International Energy Agency, 2021). These increases are leading to global warming and climate change, resulting in extreme weather events (UnitedNations, 2021). Decentralizing the energy system is one way to fight climate change. Decentralized provision of clean energy and the transition toward a circular economy are fundamental processes to reduce the total CO_2 emissions (European Commission, 2020). Solar power can potentially cover 20 % of the electricity demand of the European Union by 2040 (European Commission, 2022). However, solar power is not the only technology with decentralization potential. Decarbonization across multiple energy sectors is mandatory to reach the goals of the Paris agreement (Umwelt, Energie, Mobilität, Innovation und Technologie Bundesministerium für Klimaschutz, 2022). Therefore, decentralized technologies that can produce energy forms other than electricity, such as heat pumps for heat provision, are also required in decentralized energy systems. Decentralization must go hand in hand with sustainability considerations in resource utilization. Water utilization in the energy system in particular is a significant aspect of the water-energy nexus. The sustainability of decentralization can be evaluated based on its contribution to the United Nations Sustainable Development Goals (SDGs) (United Nations, 2022). Furthermore, consumers are a central part of decentralization in the energy system. Thus, incentives are required to encourage consumers to contribute to the SDG. Local sustainable communities (LSC) are introduced to provide such encouragement.

LSCs are a combination of sustainable communities (SCs) and local energy communities (ECs). 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). Moreover, SCs are established to efficiently use natural resources (Egan, 2004). LSC concepts can include energy, resources and other commodities. However, the formation and implementation of an SC rely on the participants' own 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 partic-

* Corresponding author.
E-mail address: maldet@eeg.tuwien.ac.at (M. Maldet).

https://doi.org/10.1016/j.cles.2023.100106
Received 7 December 2022; Received in revised form 30 December 2023; Accepted 31 December 2023
Available online 4 January 2024

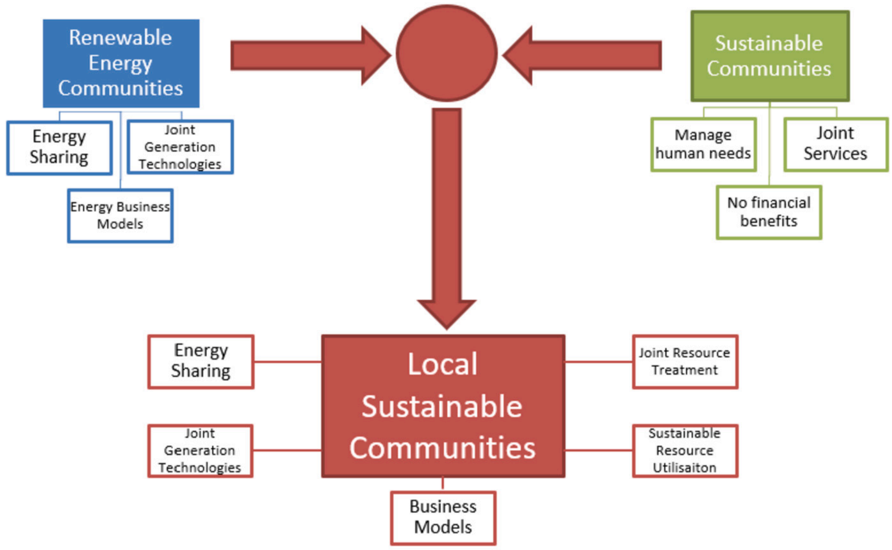

Fig. 1. LSC definition.

ipation and formation should not be financial gain, cost savings can be generated by the provided incentives. The European framework differs between citizen ECs for joint use of energy without geographical limitations (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, 2019) and renewable ECs for joint use of renewable energy at the local or regional level (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, 2018). An LSC is a combination of renewable ECs and SCs. 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 by promoting efficient consumer application of such. Therefore, the major goal of LSC business model introduction is the efficient utilization of local resources and locally generated energy. Improving local energy and resource utilization efficiency should thus contribute to the transition to a clean local energy system. An overview of the LSC concept is provided in Fig. 1.

LSCs consider different opportunities for local sustainable development. Joint clean energy generation technologies and energy sharing models are provided to participants of LSCs for more efficient use of clean, local energy. Furthermore, sustainable resource utilization models such as the joint treatment and management of resources at the local level are implemented in LSCs. Such models should provide incentives for participants to use their local resources such as waste and water more efficiently and avoid the waste of resources without gaining further value from them. Thus, LSCs consider sustainability mainly for sustainable energy and resource utilization at the consumer level.

To investigate the impact of LSC formation and LSC business models, LSC concepts are applied to the Gemeinschaftlich Wohnen Die Zukunft (GeWoZu) community in Waidhofen/Ybbs in lower Austria (Verein GeWoZu, 2020). The GeWoZu is an SC because participation offers no direct financial advantage in everyday life operations. Business models such as service provisions, technology provisions and incentives for resource reduction are applied in the community. Furthermore, trading among community participants is enabled and joint resource treatment is examined. Water is mainly considered from the water-energy nexus consumers' perspective. Treated waste on the other hand is considered within the LSC system boundaries only. A mixed integer linear optimization problem (MILP) of the considered LSC is established for the analyses. An optimization model on sector coupling in communities with additional resource utilization is developed in that context. 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 sustainable decentralized energy system operations. The introduction of LSC should provide incentives for sustainable resource utilization. The impact assessment of services on LSC participants and service providers, who are also members of the LSC, is another core objective. The analyses in this work aim to assess the contributions of LSCs to the SDGs. Thus, the following research questions are raised:

- How can an LSC contribute to the UN SDGs?
- What benefits will potential LSC members receive if they participate in an LSC?
- How can LSC business models promote sustainable energy and resource use within an LSC?
- How do different LSC services affect LSC operations?

The paper is organized as follows. Section 2 presents literature on ECs, SCs and resource utilization. Section 3 provides the applied method and the case study. Section 4 shows the major results of the analyses. Addressing the research questions, Section 5 discusses the results further. Finally, Section 6 provides the conclusions of the major findings.

2. State of the art

Combining local ECs and SCs requires a detailed literature review on existing analyses on both topics. Section 2.1 addresses ECs while Section 2.2 presents a literature review on SCs. The introduction of an LSC considers the implementation of resource utilization. Section 2.3 presents the state of the art on this topic and Section 2.4 concludes the chapter with novelties and progress beyond the state of the art.

2.1. Energy communities

Citizen ECs (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, 2019) and renewable ECs (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, 2018) are a widely addressed topic in the EU due to the corresponding guidelines. However, Maldet, Revheim, Schwabeneder, Lettner, del Granado, Saif, Löschenbrand and Khadem (2022) states that EC implementation varies across EU member countries. Azarova et al. (2019) highlighted a different performance, as they found that country-specific norms must be considered in EC implementation. Lowitzsch et al. (2020) proposed enabling a framework for the widespread adoption of ECs. Young and Brans (2017) defined frameworks that highlight the role of actors, where participants of ECs need to become co-owners. However, Gui and MacGill (2018) showed that EC implementation is dependent not only on the existing framework but also on the goals and interests of different communities. In that context, Hoicka et al. (2021) outlined complementarity and proximity as aspects to be considered in establishing EC. Several analyses investigated the implementation potential of ECs across Europe. Mihajlov (2010) proposed implementing local energy markets in southeastern Europe. Dóci et al. (2015) examined the change in the Dutch energy system by the connection of actors in ECs. Gallego-Castillo et al. (2021) found that optimal sizing in ECs leads to economic savings and observed positive impact in Spain.

ECs are expected to have and impact on the European energy systems. Thus, various studies introduce new business models to promote ECs. 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. However, little research has been conducted on consumers' preferences yet. Silvestre et al. (2021) described the necessity of energy management systems and smart contracts in implementing EC business models. Business models consider not only consumer involvement but also technology provision such as PV and batteries 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.

As Fouladvand et al. (2022) mentioned, ECs are usually dominated by electricity generation and sharing. Romero-Rubio and de Andrés Díaz (2015) outlined the importance of promoting sectors beyond electricity. Backe et al. (2021) examined average European electricity cost reductions of 3 % by sector coupling. Papatsounis et al. (2022) provided an overview of thermal ECs, finding a lack of district heating grids and thermal storage. Abdalla et al. (2021) found a that using thermal energy-sharing models had a positive environmental impact. Furthermore, Bartolini et al. (2020) examined multi-energy systems as the most cost-efficient solution in ECs. Good and Mancarella (2019) and Liu et al. (2022) underlined the importance of multi-energy storage. Moreover, Tostado-Véliz et al. (2022) included electric vehicles and flexibilities in their study on ECs.

2.2. Sustainable communities

SCs differ from ECs in several essential aspects. They consider not only energy, but also other human needs such as food, as mentioned by Lopez et al. (2020). According to Lu et al. (2017) SCs primarily aim to shift sustainability and contribution to the SDGs to the local level. Their study found that this shift can be achieved by optimizing resource allocation and updating local infrastructure. However, SCs can also have similar targets as ECs, such as carbon reduction, as presented by Chen and Kuo (2016). According to Nogueira et al. (2022), SCs are important micro agents in contributing to the UN SDGs. Aguiñaga et al. (2018) introduced entrepreneurs, NGOs and citizens as key stakeholders in SCs. The key success factors of SCs were identified by Morris et al. (2018) and these are government, experience, efficient management and sustainability. Broska (2021) identified the need to live a sustainable lifestyle and to fight against climate change as the main community motives. The implementation of SCs is not strictly defined and can thus be executed differently in various communities. Xia et al. (2015) introduced rating tools for SCs in Australia, as they are needed for decision-making processes in SCs. Moreover, Santillan et al. (2022) developed a framework for community and infrastructure planning, providing important guiding principles.

System boundaries between SCs and ECs partly overlap, as energy is a significant aspect in sustainable development, as presented by Baños et al. (2011). A case study by Orehounig et al. (2014) outlined the importance of energy in SC because 86 % of the CO_2 emissions in the considered city could be reduced by integrating distributed energy systems. Different frameworks for energy in SCs are developed. Vallecha et al. (2021) introduced a conceptual framework for energy systems in SCs, while the framework of Hippel et al. (2011) focused on energy security. Haas et al. (2008) investigated transition paths to reduce the waste of services and energy-related emissions. Similar to ECs, energy operation in SCs can be promoted by technology utilization. Rae and Bradley (2012) examined the implementation of small-scale energy systems based on renewable sources, with technology use to connect humans with their environment being a major aspect. Moreover, Hasan and Dincer (2019) introduced a renewable energy system to SC, where wind turbines provided major positive contributions to the SC. Energy utilization in SCs is not limited to electricity, as presented in the examination on geothermal energy integration by Ozturk and Dincer (2021).

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.

2.3. Resource utilization

Resource utilization can have a fundamental role in sector coupling, as presented by Maldet, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer (2022). 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.

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. Vu et al. (2022) highlighted the water recovery potential of sewage. Amulen et al. (2022) investigated the high potential of waste incineration energy recovery in their case study. Aside from, sewage sludge has a high energy recovery potential, as found by Singh et al. (2020) and Peccia and Westerhoff (2015). Treatment of resources for energy recovery can further reduce waste quantities leading to positive environmental impacts, as stated by Zaharioiu et al. (2021).

Resource utilization can also 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

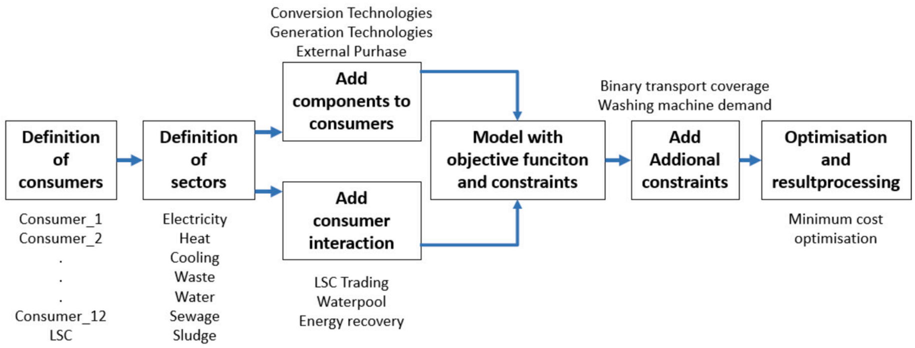

Fig. 2. Model Workflow.

SCs, as presented by Seyranian et al. (2015). According to Otaki et al. (2017), more opportunities could arise through comparison and feedback mechanisms for water consumption in communities. 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.

2.4. Novelties and progress beyond the state of the art

SCs and ECs are widely addressed topics in existing literature. However, a combination of SCs and ECs, EC business models and SC implementation with consideration of the UN SDGs has not yet been examined. Furthermore, service and technology provisions across multiple sectors have been investigated. Yet a combination of services across numerous sectors with potential business models to promote services to communities has not been addressed. Many open-source models such as the local flexibility optimization model of Schwabeneder et al. (2021) and the sector coupling optimization framework of Hilpert et al. (2018) already provide ECs and sector coupling functionalities. Yet, no appropriate modeling framework that also considers resource utilization exists for sector-coupled community investigations in decentralized energy systems.

The novelties and contributions beyond the state of the art of this work can be summarized as follows:

i) It introduces LSCs as a combination of ECs and SCs
ii) It investigates technology and service provision business models across multiple sectors on the community level
iii) It analyzes water reduction business models with predefined limitation agreements
iv) It implements a model extension of the “Resource Utilization in Sector coupling (RUTIS)” framework (Maldet, 2022) to sector coupling in communities

3. Materials and method

An optimization model on decentralized sector coupling implementation in communities was developed to elaborate the research questions. Therefore, the RUTIS model (Maldet, 2022) which was presented in Maldet, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer (2022), was extended to trading and business model functionalities.

3.1. Investigation setup

The optimization model is applied to the demo site 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 setup are presented in Table A.7 in the Appendix. Demand assumptions are made for the consumers, as presented in Table A.8. 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 1.

3.1.1. LSC model equations

General model functionalities were presented by Maldet, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer (2022). The proposed framework is extended to LSC operations and business models. The application of the framework in community investigations is presented in Fig. 2.

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

$$min(z) = min(c^{\text{tot}}) \tag{1}$$

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, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer, 2022).

The total costs without an LSC establishment consist of technological operational costs, purchase costs from external sources and disposal costs, as presented in Equation (2). Total costs for all consumers are calculated by a summation of individual consumers costs (Equation (3)).

$$c_{i,t}^{\text{tot,noLSC}} = \sum_{j\in S}(\sum_{l\in \mathcal{T}} c_{i,j,l,t}^{\text{O\&M}} + \sum_{(k\in \mathcal{E}} (c_{i,j,k,t}^{\text{purchase}} + c_{i,j,t}^{\text{disposal}})) \quad \forall i \in C \tag{2}$$

$$c^{\text{tot,base}} = \sum_{t\in T}\sum_{i\in C} c_{i,t}^{\text{tot,noLSC}} \tag{3}$$

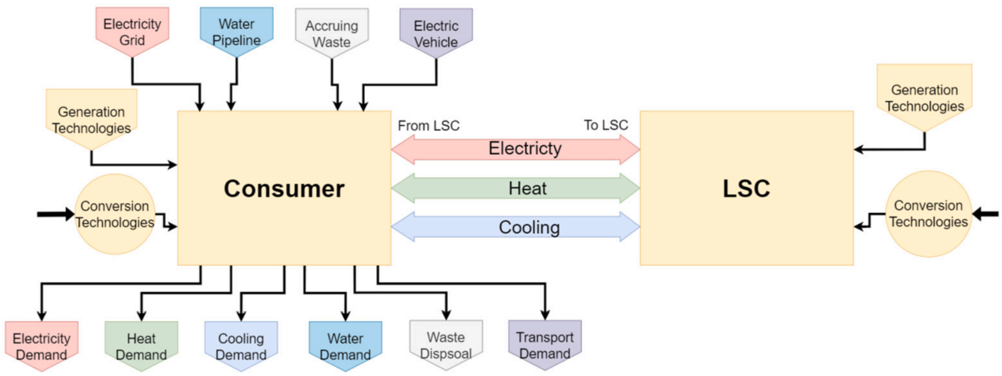

Fig. 3. Introduction LSC operator.

Technological operational costs are set together of costs for technological inputs and outputs (Equation (4)), while purchase costs are determined based on the procured amount $x^{\text{purchase}}_{i,k,t}$ and the price of the external source $\Pi^{\text{purchase}}_{k,t}$ (Equation (5)).

$$c^{\text{O\&M}}_{i,l,t} = \sum_{Inputs} C^{\text{in}}_{l,t} \cdot x^{\text{in}}_{i,l,t} + \sum_{Outputs} C^{\text{out}}_{l,t} \cdot x^{\text{out}}_{i,l,t} \quad \forall i \in \mathcal{C}, l \in \mathcal{T} \tag{4}$$

$$c^{\text{purchase}}_{i,k,t} = \Pi^{\text{purchase}}_{k,t} \cdot x^{\text{purchase}}_{i,k,t} \quad \forall i \in \mathcal{C}, k \in \mathcal{E} \tag{5}$$

Consumers can feed excess electricity into the grid to generate revenues, as presented in Equation (6).

$$rev^{\text{feedin}}_{i,Elec,t} = \Pi^{\text{feedin}}_{Elec,t} \cdot x^{\text{feedin}}_{i,Elec,t} \quad \forall i \in \mathcal{C} \tag{6}$$

Basic model assumptions consider several constraints, which emerge due to technology limitations (Equation (7)) and input-output relations of conversion technologies (Equation (8)).

$$x_{l,t} \leq X^{\text{max}}_{l} \quad \forall l \in \mathcal{T} \tag{7}$$

$$x^{\text{out}}_{l,t} = F^{\text{conversion}}_{l,t} \cdot x^{\text{in}}_{l,t} \quad \forall l \in \mathcal{T} \tag{8}$$

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 (9).

$$X^{\text{Demand,noLSC}}_{i,j,t} = \sum_{k\in\mathcal{E}} x_{i,j,k,t} + \sum_{l\in\mathcal{T}} x_{i,j,l,t} \quad \forall i \in \mathcal{C}, j \in \mathcal{S} \tag{9}$$

Further constraints are implemented in the form of storage equations (Equation (10)), with the corresponding initial value according to Equation (11). Predefined emptying periods can be defined, thereby leading to additional restrictions. These constraints define the time steps at which storage outflows are allowed (Equations (12) and (13)).

$$soc_t = \eta^{\text{sb}} \cdot soc_{t-1} + \eta^{\text{in}} \cdot x^{\text{in}}_t - \frac{x^{\text{out}}_t}{\eta^{\text{out}}} \tag{10}$$

$$soc_{t=0} = SOC^{\text{start}} \tag{11}$$

$$soc_t = 0 \quad \forall t \in \mathcal{D} \tag{12}$$

$$x^{\text{out}}_t = 0 \quad \forall t \notin \mathcal{D} \tag{13}$$

These equations account for consumers and apply even if no LSC is formed.

3.1.2. Introduction of the LSC operator

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 Fig. 3.

The model methodology changes, as the balance rule for consumers is extended by LSC purchase $x^{\text{LSC2cons}}_{i,j,t}$ and sale $x^{\text{cons2LSC}}_{i,j,t}$, as presented in Equation (14).

$$X^{\text{Demand,LSC}}_{i,j,t} = X^{\text{Demand,noLSC}}_{i,j,t} + x^{\text{LSC2cons}}_{i,j,t} - x^{\text{cons2LSC}}_{i,j,t} \tag{14}$$

The costs for the consumers are extended by LSC purchase costs and LSC sale revenues (Equation (15)).

$$c^{\text{tot,LSC}}_{i,j,t} = c^{\text{tot,noLSC}}_{i,j,t} + x^{\text{LSC2cons}}_{i,j,t} \cdot \Pi^{\text{LSC2cons}}_{i,j,t} - x^{\text{cons2LSC}}_{i,j,t} \cdot \Pi^{\text{cons2LSC}}_{i,j,t} \tag{15}$$

The LSC has its own balance rule, which is implemented as an additional constraint in Equation (16). 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.

$$\sum_{k\in\mathcal{E}} x_{LSC,j,k,t} + \sum_{l\in\mathcal{T}} x_{LSC,j,l,t} + \sum_{i\in C} x^{\text{cons2LSC}}_{i,j,t} = \sum_{i\in C} x^{\text{LSC2cons}}_{i,j,t} \tag{16}$$

LSC costs consist of procurement costs, conversion technology operational costs and disposal costs (Equation (17)). Costs for consumer purchases and revenues for consumer sales must also be considered, resulting into total costs according to Equation (18).

$$c^{\text{own}}_{LSC,j,t} = \sum_{l\in\mathcal{T}} c^{\text{O\&M}}_{LSC,j,l,t} + \sum_{k\in\mathcal{E}} c^{\text{purchase}}_{LSC,j,k,t} + c^{\text{disposal}}_{LSC,j,t} \tag{17}$$

$$\begin{aligned} c^{\text{total}}_{LSC,j,t} = c^{\text{own}}_{LSC,j,t} &+ \sum_{i\in C} x^{\text{cons2LSC}}_{i,j,t} \cdot \Pi^{\text{cons2LSC}}_{i,j,t} \\ &- \sum_{i\in C} x^{\text{LSC2cons}}_{i,j,t} \cdot \Pi^{\text{LSC2cons}}_{i,j,t} \end{aligned} \tag{18}$$

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

3.1.3. 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 $\Pi^{\text{LSC2elec,energy}}_{Elec,t}$, grid charges $\Pi^{\text{grid}}_{Elec,t}$ and additional fees $\Pi^{\text{surcharge}}_{Elec,t}$, as presented in Equation (19).

$$\Pi^{\text{LSC2elec}}_{Elec,t} = \Pi^{\text{LSC2elec,energy}}_{Elec,t} + \Pi^{\text{grid}}_{Elec,t} + \Pi^{\text{surcharge}}_{Elec,t} \tag{19}$$

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, as described in Equation (20).

$$\Pi^{\text{LSC2elec,energy}}_{Elec,t} = \frac{\Pi^{\text{purchase}}_{Elec,t} + \Pi^{\text{feedin}}_{Elec,t}}{2} \tag{20}$$

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, as presented in Equation (21).

$$\Pi^{\text{elec2LSC}}_{Elec,t} = \Pi^{\text{LSC2elec,energy}}_{Elec,t} \tag{21}$$

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 with Equation (22).

$$p^{\text{max,elecgrid}}_{LSC} \geq \frac{\sum_{i \in C} q^{\text{gridpurchase}}_{i,Elec,elecgrid,t} + q^{\text{gridpurchase}}_{LSC,Elec,elecgrid,t}}{\Delta t} \quad \forall t \in T \tag{22}$$

The maximum power is multiplied by a power-based price, as presented in Equation (23), and the resultant costs are added to the total costs. The LSC operator pays power-based costs. Expense sharing depends on the LSC agreement.

$$c^{\text{power}}_{LSC,Elec} = p^{\text{max,elecgrid}}_{LSC} \cdot \Pi^{\text{power}}_{Elec} \tag{23}$$

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.

$$\Pi^{\text{LSC2energy}}_{j,t} = \Pi^{\text{LSC2energy,energy}}_{j,t} + \Pi^{\text{grid}}_{j,t} \quad \forall j \in Heat, Cool \tag{24}$$

$$\Pi^{\text{energy2LSC}}_{j,t} = \Pi^{\text{energy2LSC,energy}}_{j,t} \quad \forall j \in Heat, Cool \tag{25}$$

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.

3.2. 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.

3.2.1. 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. The amount of sewage emerging from water treatment is determined with Equation (26). Furthermore, the amount of potentially recovered water is calculated with Equation (27), while the amount of emerging sludge is calculated with Equation (28).

$$v^{\text{sewage}}_{LSC,t} = \sum_{i \in Consumers} Share^{\text{sewage}} \cdot d^{\text{water}}_{i,t} \tag{26}$$

$$v^{\text{water,LSC}}_{LSC,t} = K^{\text{waterrecovery}} \cdot v^{\text{sewage}}_{LSC,t} \tag{27}$$

$$v^{\text{sludge}}_{LSC,t} = \frac{Ct^{\text{sludge}}}{\rho^{\text{sludge}}} \cdot v^{\text{sewage}}_{LSC,t} \tag{28}$$

Sludge is stored and transported to treatment plants, where electricity and heat can be recovered by sludge incineration (Equation (29)) and untreated sludge is disposed.

$$q^{\text{sludgecomb}}_{LSC,j,t} = \eta^{\text{sludgecomb}}_{j} \cdot v^{\text{sludge}}_{LSC,t} \cdot H^{\text{sludge}}_{S} \quad \forall j \in Elec, Heat \tag{29}$$

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, whereas no additional costs for financial gains of the treatment plant operator are charged. This results in the sewage treatment cost Equation (30).

$$c^{\text{sewagechain}}_{LSC} = c^{\text{sewagetreat}} + c^{\text{storage,sludge}} + c^{\text{sludgetransport}} + c^{\text{sludgecomb}} + c^{\text{sludgedisposal}} \tag{30}$$

The required electricity for sewage treatment must be (virtually) provided by the LSC operator, as presented in Equation (31).

$$q^{\text{sewagetreat,elec}}_{LSC,t} = K^{\text{sewagetreat,Elec}} \cdot v^{\text{sewage}}_{LSC,t} \tag{31}$$

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.

3.2.2. Water demand coverage

The LSC members agree to reduce their total water demand $d^{\text{water}}_{i,t}$. These agreements include a limitation of water purchase options. The different water coverage options are presented in Equation (32).

$$d^{\text{water}}_{i,t} = v^{\text{pipe,limited}}_{i,t} + v^{\text{water,LSC}}_{i,t} + v^{\text{poolpurchase}}_{i,t} + v^{\text{pipe,excess}}_{i,t} \tag{32}$$

Conventional water purchase $v^{\text{pipe,limited}}_{i,t}$ is limited to half of the predefined total water demand $D^{\text{water}}_{i,t}$. For limited pipeline purchase, conventional water prices $\Pi^{\text{pipe,water}}$ are charged. Another option is to purchase water from the LSC operator ($v^{\text{water,LSC}}_{i,t}$) 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 $v^{\text{poolpurchase}}_{i,t}$ 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 $\Pi^{\text{waterpool}}$ (Equation (33)).

$$d^{\text{water}}_{i,t} = D^{\text{water}}_{i,t} - v^{\text{water2pool}}_{i,t} \tag{33}$$

Water reduction is limited by consumers' incentives (Equation (34)). The limitation is implemented by a limiting factor K_{WFF}, representing a willingness for water reduction flexibility (WFF).

$$d^{\text{water}}_{i,t} \geq D^{\text{water}}_{i,t} \cdot (1 - K_{WFF}), \quad K_{WFF} \in [0, 0.5] \tag{34}$$

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 (35).

$$Prob_{WFF} = 0.4 \cdot e^{-6.2 \cdot K_{WFF}} \tag{35}$$

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.

3.3. LSC waste model

LSC business models aim to use waste as a valuable resource. This section introduces waste energy recovery models and reduction models.

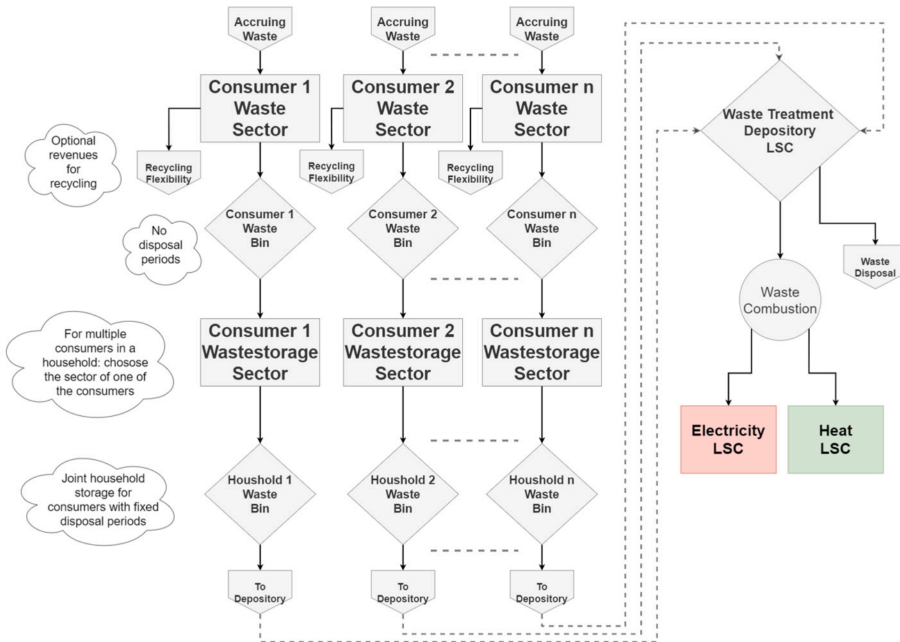

Fig. 4. Waste treatment Chain.

A crucial consideration is that waste treatment and market models are applied only within the system boundaries of the LSC.

3.3.1. 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 Fig. 4.

The LSC operator needs to shoulder costs for transport and treatment processes, as presented in Equation (36).

$$c^{\text{wastechain}}_{LSC} = c^{\text{wastetransport}} + c^{\text{wastecomb}} + c^{\text{wastedisposal}} \tag{36}$$

The recovered energy is equivalent to Equation (29). The only difference is that waste is incinerated instead of sludge.

3.3.2. 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 (37)) determined based on the survey of Statista (2022b). It is described by the willingness for reduction and recycling (WFR) K_{WFR}.

$$Prob_{WFR} = -1.1 \cdot K^3_{WFR} + 8.2 \cdot K^2_{WFR} + 0.4 \cdot K_{WFR} + 0.05 \tag{37}$$

The recycled waste is limited by the product of the WFR and the total consumers' waste demand $D^{\text{waste}}_{i,t}$, as presented in Equation (38).

$$m^{\text{recycled}}_{i,t} \leq K_{WFR} \cdot D^{\text{waste}}_{i,t}, \quad K_{WFR} \in [0, 0.4] \tag{38}$$

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 (39). This equation considers the usable recovered energy $\eta^{\text{wastecomb}}_{usable}$, waste heating value H^{waste}, combustion efficiencies $\eta^{\text{wastecomb}}_{j}$, operational costs of heat pump and waste combustion, electricity grid purchase costs $C^{\text{purchase}}_{Elec,grid}$ and the coefficient of performance of the heat pump $COP^{\text{mean}}_{heatpump}$.

$$\begin{aligned}\Pi^{\text{wastemarket}} = \eta^{\text{wastecomb}}_{usable} \cdot H^{\text{waste}} \cdot (\eta^{\text{wastecomb}}_{Elec} \cdot C^{\text{purchase}}_{Elec,Grid} \\ + \frac{\eta^{\text{wastecomb}}_{Heat}}{COP^{\text{mean}}_{heatpump}} \cdot C^{\text{purchase}}_{Elec,Grid} + \eta^{\text{wastecomb}}_{Heat} \cdot C^{\text{O\&M}}_{Heatpump} \\ -(\eta^{\text{wastecomb}}_{Elec} + \eta^{\text{wastecomb}}_{Heat}) \cdot C^{\text{O\&M}}_{Wastecomb})\end{aligned} \tag{39}$$

3.4. 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.

3.4.1. 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, resulting in Equation (40). Emissions are caused by electricity grid purchase, waste- and sludge transport, incineration, disposal processes and sewage treatment.

$$\begin{aligned}em^{\text{tot}}_{LSC,t} = \sum_{i \in C} (em^{\text{elgrid}}_{i,Elec,t} + em^{\text{wastetransport}}_{i,Waste,t}) \\ + em^{\text{elgrid}}_{LSC,Elec,t} + em^{\text{wastecomb}}_{LSC,Waste,t} + em^{\text{wastedisposal}}_{LSC,Waste,t} \\ + em^{\text{sewagetreatment}}_{LSC,Sewage,t} + em^{\text{sludgetransport}}_{LSC,Sludge,t} \\ + em^{\text{sludgecomb}}_{LSC,Sludge,t} + em^{\text{sludgedisposal}}_{LSC,Sludge,t}\end{aligned} \tag{40}$$

Extensions consider CO_2 prices that are multiplied by the total emissions, resulting in the corresponding emission costs (Equation (41)).

$$c^{\text{emissions}} = \sum_{t \in T} \Pi^{\text{CO2}} \cdot em^{\text{total}}_{LSC,t} \tag{41}$$

3.4.2. 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 (15), resulting in Equation (42).

$$c^{\text{tot,consumers}} = \sum_{t \in T} \sum_{i \in C} \sum_{j \in S} c^{\text{total,LSC}}_{i,j,t} + c^{\text{waterdemand}}_{i,Water,t} \quad (42)$$

LSC costs from Equation (18) are extended by power costs and costs within the sewage and waste chain in Equation (43).

$$c^{\text{tot,LSC}} = \sum_{t \in T} \sum_{j \in S} c^{\text{tot}}_{LSC,j,t} + c^{\text{power}}_{LSC,Elec} + c^{\text{sewagechain}}_{LSC} + c^{\text{wastechain}}_{LSC} \quad (43)$$

Both are summed to form the total model costs in Equation (44).

$$c^{\text{tot}} = c^{\text{tot,consumers}} + c^{\text{tot,LSC}} \quad (44)$$

3.4.3. 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 factor 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.

3.5. 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 research questions are adequately examined.

3.5.1. Setup

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 behaviors are examined. The final scenarios analyze the impact and opportunities due to industry services. The workflow of the case study is presented in Fig. 5.

The available services in the case study scenarios are summarized in Table 1.

LSC key performance indicators (KPIs) are defined for the impact assessment of the scenarios. An overview and the definition of the KPIs are presented in Table 2.

3.5.2. Model validation

The basic model validation of the RUTIS model was presented in Maldet, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer (2022). Model validation of the functionality extension was conducted in the course of the case study. With the gradually altered model setup, model functionalities could be validated by gradual LSC performance improvement with the introduction of additional services. Furthermore, investigations with service omission derive the expected behavior, thereby underlining the validity of the model. The model validation is described in detail in the Appendix.

4. Results

The main results of the analyses are presented in this section. Section 4.1 shows the results on LSC impacts and Section 4.2 presents the effects on the LSC services. Section 4.3 and 4.4 provide the results for resource markets and external service provisions.

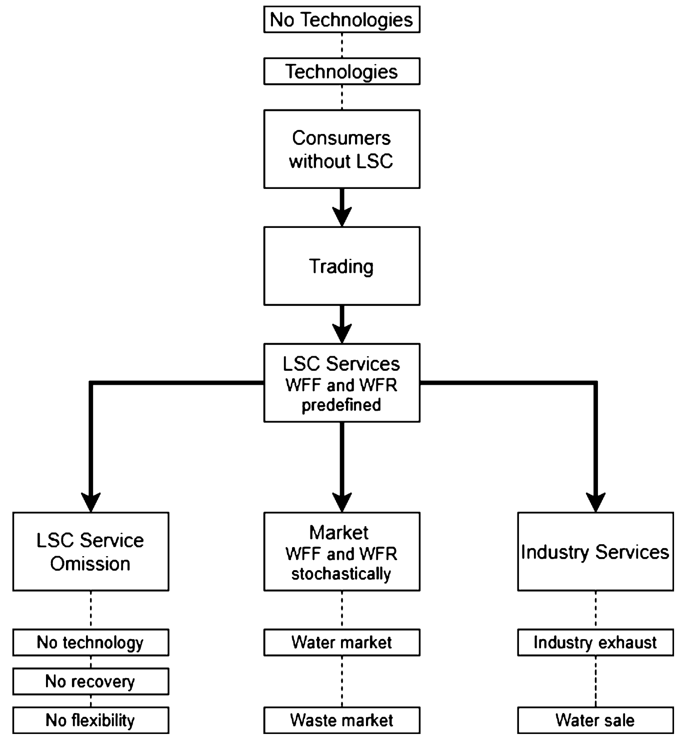

Fig. 5. Case study.

Table 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 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

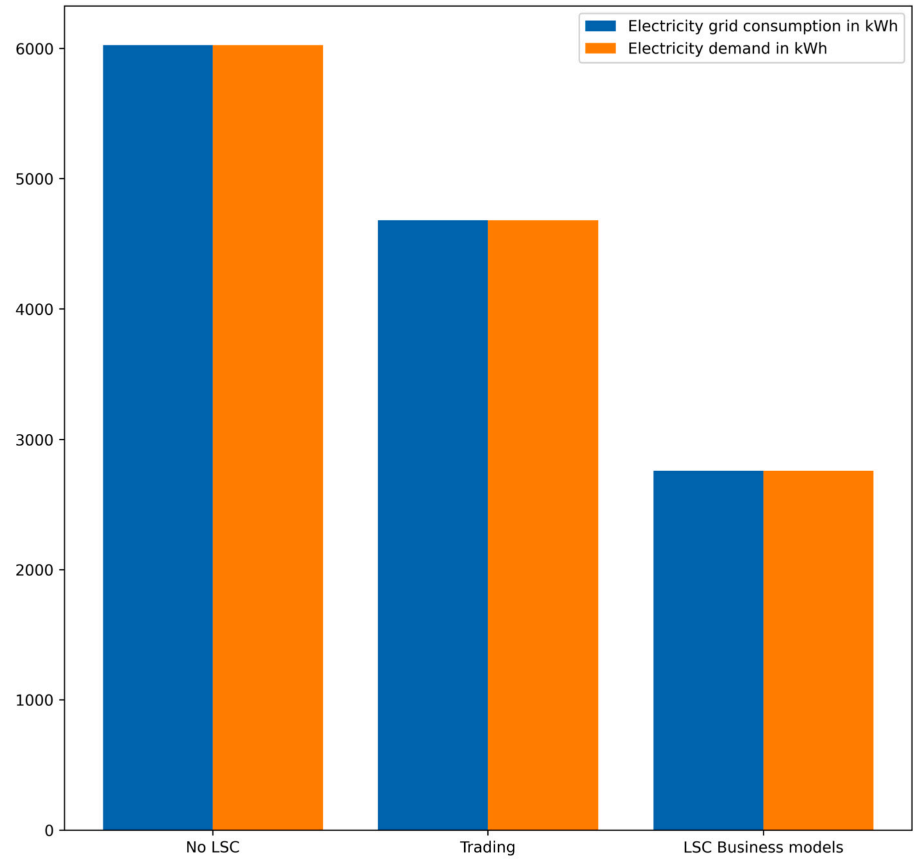

Fig. 6. Consumer electricity grid input.

4.1. 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 €.

Figs. 6, 7 and 8 present 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.

The heat map in Fig. 9 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.

Table 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

4.2. 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 3 and 4.

Consumers cannot sell energy to the LSC without their own technologies. Decreased decentralization 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.

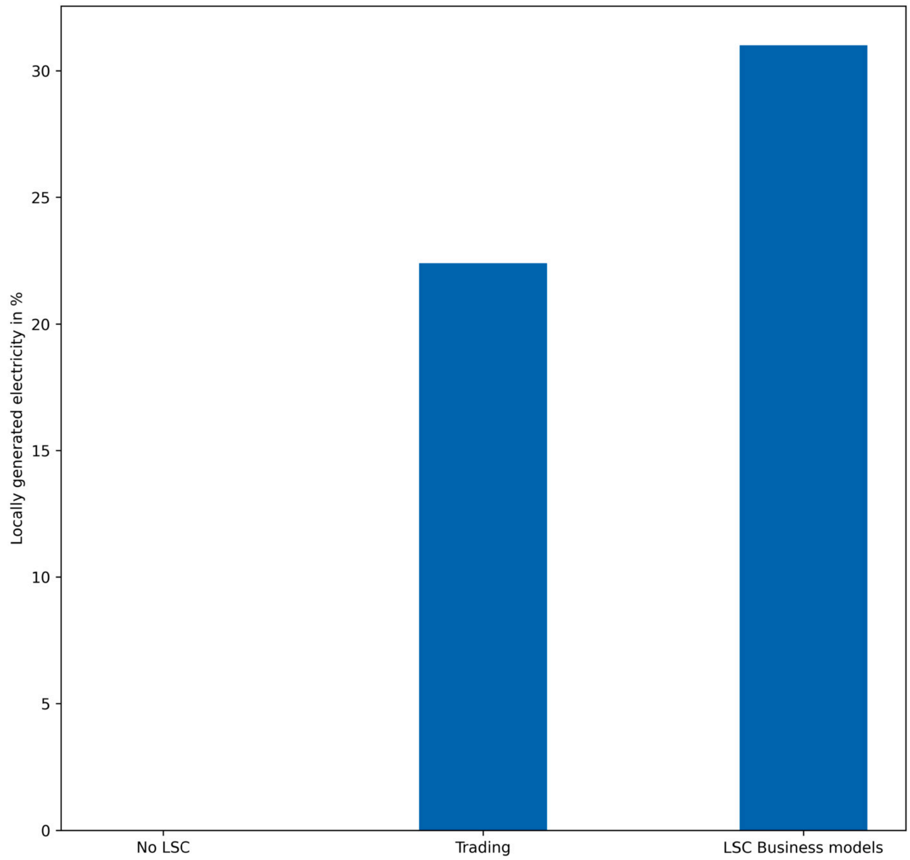

Fig. 7. Locally generated electricity use.

Table 4
Service omission: resource KPIs.

Scenario	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 waterpurchase 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

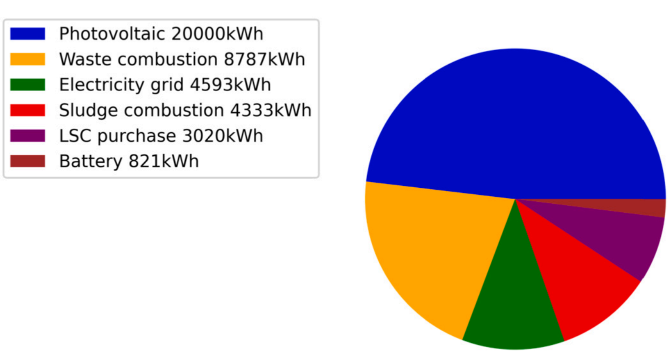

Fig. 8. LSC operator electricity input share.

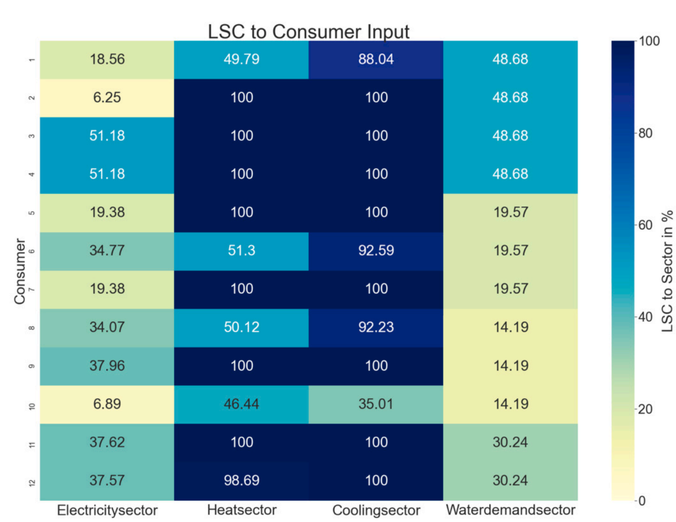

Fig. 9. LSC heatmap.

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 Fig. 10, omitting energy recovery leads to the highest cost increase, followed by technology omission.

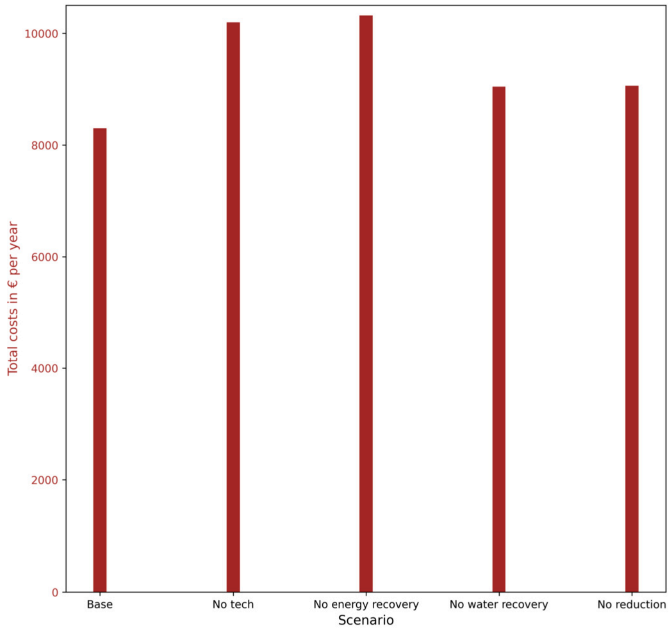

Fig. 10. Service omission: costs.

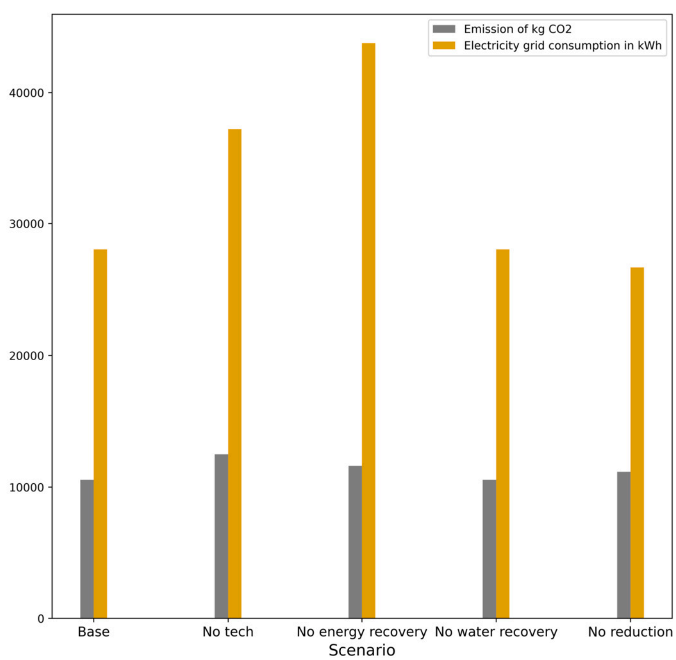

Fig. 11. Service omission: emissions and grid consumption.

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 Fig. 11.

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.

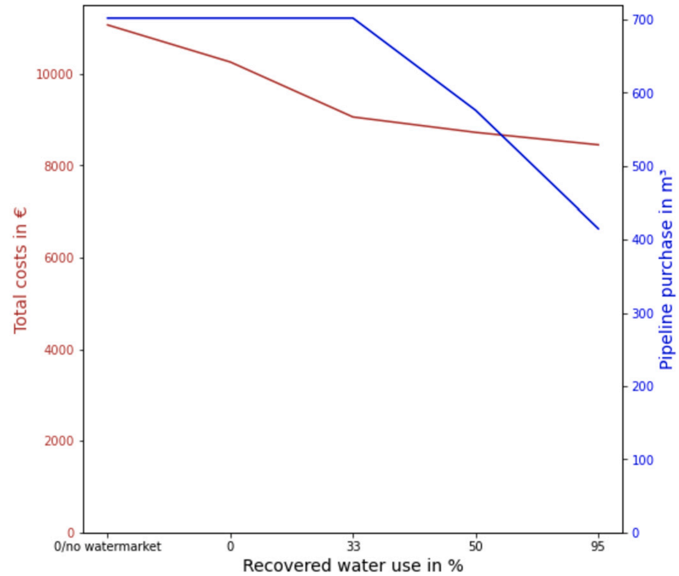

Fig. 12. Watermarket overall impact.

4.3. *Introduction of resource markets*

In this section, market investigations are further assessed, beginning with the water market in Section 4.3.1 followed by the waste market in Section 4.3.2. Different WFF and WFR for different consumers are assumed in the analyses.

4.3.1. *Water consumption rights trading*

Water market impact is investigated by conducting a sensitivity analysis of recovered water from sewage treatment. Fig. 12 presents the effect of the water market and recovered water on the total costs and pipeline purchase.

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. At a higher reduction than 33 % additional water costs can be saved. However, the savings are lower because, at higher rates, the conventional pipeline purchase term with lower costs is avoided. The avoidance of this term results in lower cost savings than the avoidance of the excess purchase term. The impact on the consumers is presented in Fig. 13.

The implementation of water recovery positively affects consumers' costs. 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.

4.3.2. *Waste recycling and reduction markets*

The waste market price is decreased in a sensitivity analysis, starting from the equilibrium price of Equation (39) ($\Pi^{wastemarket} = 0.1457$ €/kg). No recycling is conducted in situations with lower efficient waste market prices, as presented in Fig. 14. 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 Fig. 15.

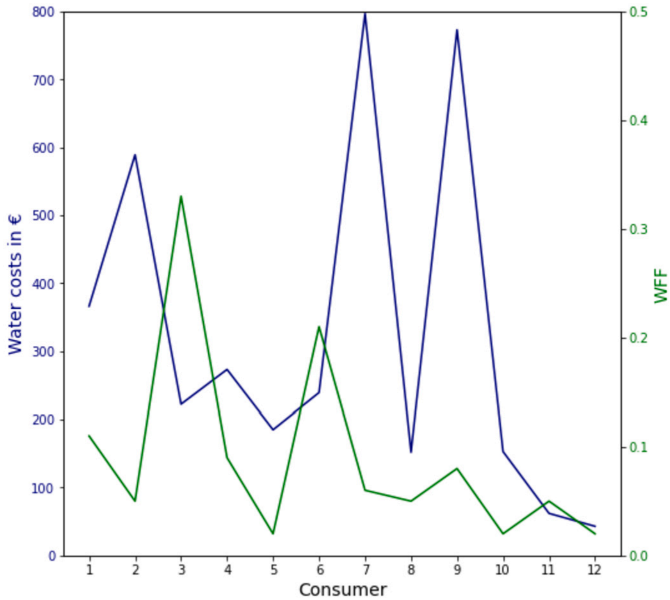

Fig. 13. Watermarket consumer impact.

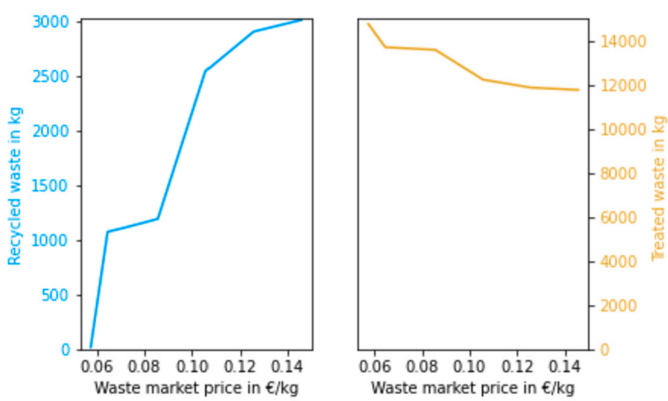

Fig. 14. Wastemarket recycling.

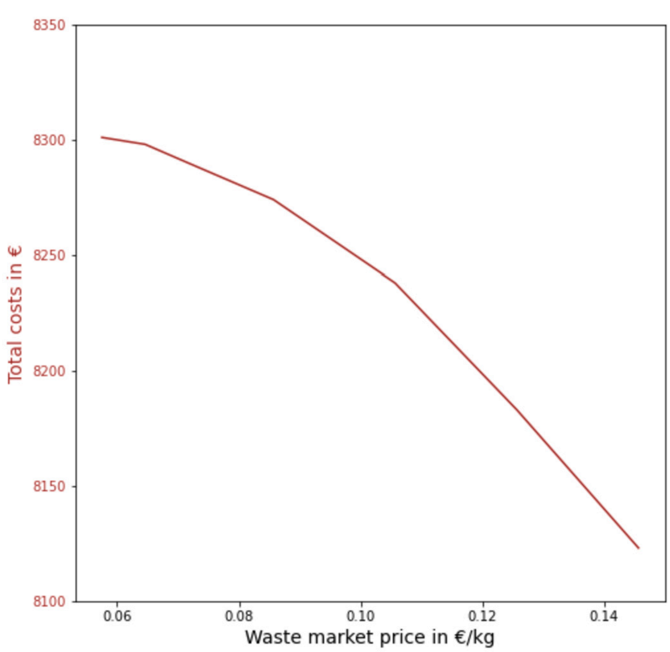

Fig. 15. Wastemarket costs.

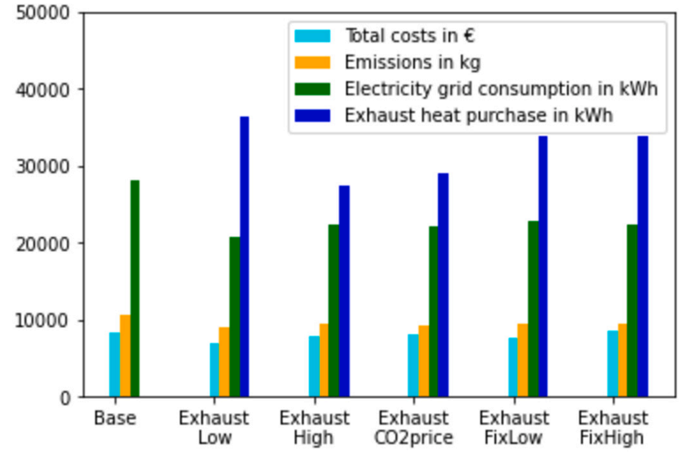

Fig. 16. Exhaust heat.

Table 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

4.4. LSC extension: external service provisions

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

4.4.1. 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 analyzed. The impact on total costs, emissions, electricity grid consumption, and the procured exhaust heat are presented in Fig. 16.

The utilization of exhaust heat is strongly dependent on the energy price. CO_2 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.

4.4.2. Greywater sale

Different market prices for greywater are assumed in the investigation. The results of the scenario analyses are presented in Table 5.

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.

5. Discussion

Building upon the results in Section 4, the significant findings of the analyses are discussed in this section. Section 5.1 discusses the benefits of LSC formation to consumers and to UN SDGs (United Nations, 2022). Section 5.2 outlines the benefits for different LSC members. Section 5.3 provides the impact and suitability of the introduced LSC business models.

5.1. Benefits and suitability of an LSC introduction

LSCs are introduced to provide benefits for consumers and for the environment. The results in Section 4.1 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 society". 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 4.1, no resources were disposed of, because an LSC gives resources additional value in energy recovery and recycling. Resource market investigation results in Section 4.3 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. 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 (32), 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.

5.2. Benefits for different LSC members

The results in Section 4.1 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 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 in Section 4.4.1 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 in Section 4.4.2. 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, as introduced in Section 3.1.2. Finding an operator that takes all the initiatives can be the primary barrier to establishing an LSC.

5.3. LSC business models: impact and potential implementation barriers

For the business models under consideration, a distinction is made between behavior encouraging business models and service provider business models. The results in Section 4.3 present the behavior 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 in Section 4.3.1 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 analyzed in 4.3.2 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 4.1 and 4.4 can have a positive impact. However, bad agreements or contracts with service providers, such as fixed energy procurement agreements, can backfire and lead to increased costs (as presented in Fig. 16). Service options such as those in Section 4.4.2 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. 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 are considered, such business models generally have an overall positive impact on LSC participants.

6. Conclusions

This work introduces LSCs as an efficient community concept for sustainable energy and resource utilization in decentralized energy systems. The applicability of the developed LSC model is demonstrated in the demo site GeWoZu, considering service provision and consumer encouragement business models.

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 behavior and could further promote resource utilization. By providing such business models, consumers are encouraged to avoid wasting local energy and resources and thus, to operate more efficiently. Up to 31 % of the electricity demand and 34 % of the heating demand can be covered by local LSC procurement. In general, the establishment of an LSC has a positive impact by promoting actions that can lead to the establishment of a clean local energy system. 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. By providing services such as trading and energy recovery, the external electricity grid procurement can be reduced to 58 %. 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, reducing the total water pipeline procurement by 43 %. However, alternative options such as reduction and treatment tend to be in competition and they are dependent on the considered scope and defined LSC boundaries. If specific LSC behavior 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 is dependent 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. With all these aspects taken into consideration, we can conclude that 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.

A critical limitation of the approach is that it does not consider any investment costs. Technologies and services must be available in the LSC, and existing processes must be adapted. The approach has further limitations because waste is only considered a black box. Different waste shares and their impact are not considered. Moreover, trade-offs between waste markets and waste treatment can have a different and more significant effect beyond LSC boundaries. Another limitation is that grid infrastructure is not modeled. All energy recovery assignments are therefore made only virtually. This is a major limitation as the trade-off between physical flows and flows on the balance sheet can affect the LSC.

Future analyses should thus consider LSCs on a large scale and the interaction between multiple LSCs and the definition of system boundaries must be addressed. The physical position and grid infrastructure must also be further considered to assess the impact of LSCs on the energy system.

Nomenclature

Table 6
Model parameters and decision variables.

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*]
$COP_{heatpump}^{\text{mean}}$	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 sludge per m^3 sewage
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_{max}^{charge}	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
$P_{max}^{\text{industryexhaust}}$	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*]
$p_{LSC}^{\text{max,elecgrid}}$	Maximum power of grid purchase	kW
c_{LSC}^{power}	Power costs LSC	€
d^{water}	Variable water demand	m^3
$\upsilon^{\text{pipe,limited}}$	Limited pipeline purchase	m^3

Table 6 (*continued*)

$v^{water,LSC}$	Recovered water sewage treatment	m^3
$v^{poolpurchase}$	Water pool purchase	m^3
$v^{pipe,excess}$	Pipeline excess purchase	m^3
$v^{water2pool}$	Water pool feed-in	m^3
v^{sewage}	Sewage water	m^3
v^{sludge}	Sludge as by-product	m^3
$q^{sludgecomb}$	Recovered energy sludge combustion	kWh
$q^{sewagetreat,elec}$	Electricity demand sewage treatment	kWh
$em^{technology}$	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
$q^{wash,tot}$	Energy demand washing	kWh
$q^{washheat}$	Energy demand water heating	kWh
$q^{wash,recovery}$	Recovered heat washing	kWh
$q^{industryexhaust}$	Exhaust heat industry	kWh
$c^{industryexhaust}$	Cost exhaust heat purchase	€
$v^{greywater,sold}$	Greywater to water market	m^3
$v^{greywater,treated}$	Greywater treated	m^3
$rev^{greywater,sold}$	Revenues water market	€

CRediT authorship contribution statement

Matthias Maldet: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Schwabeneder:** Writing – original draft, Validation, Conceptualization. **Georg Lettner:** Resources, Project administration. **Christoph Loschan:** Writing – original draft. **Carlo Corinaldesi:** Writing – review & editing. **Hans Auer:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was conducted under the “Hybrid Local Sustainable Communities” project Green Energy Lab (2021), supported with funds from the Climate and Energy Fund, grant number 891897, and implemented in the framework of the RTI-initiative “Flagship region Energy” within the Green Energy Lab. The authors acknowledge TU Wien Bibliothek for financial support through its Open-Access Funding Program.

Appendix A. Consumer and cost assumptions

Basic assumptions on consumer configuration, technology costs and defined tariffs are presented in this section.

Table A.7 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 A.8.

Aside from consumer assumptions, technology assumptions were made. Technologies are charged their operational costs. Predefined values of the RUTIS model based on literature research were assumed for these costs. Maldet, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer (2022) provided an overview of technology O&M costs of the RUTIS model. In the model extension, different tariff assumptions were made which are presented in the Tables A.9 to A.12 for all considered sectors in the case study.

Table A.7
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 A.8
GeWoZu demand assumptions.

Number	Elec in kWh	Heat in kWh	Cooling in kWh	Waste in kg	Water in m^3
1	2300	2313	155	450	42.5
2	3000	3278	220	900	85
3	3500	4240	284	1350	127.5
4	4000	5205	350	1800	170
Source	(Weißbach, 2022)	(Rosenkranz, 2020)	(Vogel, 2018)	(Statista, 2022a)	(Jedamzik, 2022)

Table A.9
Electricity tariff assumptions.

Parameter	Identifier	Value
Energy costs	$\Pi^{LSC2elec,energy}_{Elec,t}$	13 ct/kWh
Grid costs	$\Pi^{grid}_{Elec,t}$	6.2 ct/kWh
Fiscal charge	$\Pi^{surcharge}_{Elec,t}$	1.8 ct/kWh
Feed-in tariff	$\Pi^{feedin}_{Elec,t}$	7 ct/kWh
LSC tariff	$\Pi^{LSC2elec,energy}_{Elec,t}$	10 ct/kWh
Power price	Π^{power}_{Elec}	35 €/kW

Table A.10
Heating and cooling tariff assumptions.

Parameter	Identifier	Value
Heat energy costs	$\Pi^{energy}_{Heat,t}$	4.0 ct/kWh
Heat grid costs	$\Pi^{grid}_{Heat,t}$	4.6 ct/kWh
LSC heat tariff	$\Pi^{LSC2energy,energy}_{Heat,t}$	3.5 ct/kWh
Cooling energy costs	$\Pi^{energy}_{Cool,t}$	4.0 ct/kWh
Cooling grid costs	$\Pi^{grid}_{Cool,t}$	4.6 ct/kWh
LSC cooling tariff	$\Pi^{LSC2energy,energy}_{Cool,t}$	3.5 ct/kWh

Table A.11
Water tariff assumptions.

Parameter	Identifier	Value
Conventional pipeline tariff	$\Pi^{pipeline}_{Water}$	1.5 €/m^3
Water recovery purchase tariff	$\Pi^{recovery}_{Water}$	1.125 €/m^3
Water pool purchase and feed-in tariff	$\Pi^{waterpool}_{Water}$	0.75 €/m^3
Excess purchase tariff	Π^{excess}_{Water}	3 €/m^3

Table A.12
Disposal cost assumptions.

Parameter	Identifier	Value
Waste disposal costs	$\Pi^{\text{disposal}}_{Waste}$	23 ct/kg
Waste transport costs	$\Pi^{\text{transport}}_{Waste}$	0.09 ct/kg
Sludge disposal costs	$\Pi^{\text{disposal}}_{Sludge}$	414 €/m^3
Sludge transport costs	$\Pi^{\text{transport}}_{Sludge}$	0.09 ct/m^3

Table A.13
Emission assumptions.

Technology	CO_2 Emissions	Comment
Elec. grid	0.209 kg/kWh	(Landesamt für Umwelt Brandenburg, 2018)
Waste combustion	1.1 kg/kg$_{\text{waste}}$	(IEA Bioenergy, 2013)
Waste disposal	0.382 kg/kg$_{\text{waste}}$	(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$_{\text{waste}}$	(Ritchie and Smith, 2009)

As emissions are considered, assumptions for CO2 emissions must be made which are presented in Table A.13. Grid emission factors are inconclusive because they vary over time. Basic values from Landesamt für Umwelt Brandenburg (2018) are assumed for the model analyses.

Appendix B. Technology modeling

Several services were introduced in Section 3.4.3. The method and mathematical equations are described in this section.

B.1. Carpool

A set of electric vehicles in the carpool is predefined, representing all available vehicles in the LSC.

$$\mathcal{V} = Vehicle_1, Vehicle_2, \ldots, Vehicle_n \tag{B.1}$$

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 MILP. The binary transport demand coverage is presented in Equation (B.2). The distance covered by a vehicle is represented by $s_{v,t}$.

$$D_{transport_i} = \sum_{v\in\mathcal{V}} bin_{i,v,t} \cdot s_{v,t} \quad \forall i \in C \tag{B.2}$$

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)).

$$\sum_{v\in\mathcal{V}} bin_{i,v,t} \le 1 \quad \forall i \in C \tag{B.3}$$

$$\sum_{i\in C} bin_{i,v,t} \le 1 \quad \forall v \in \mathcal{V} \tag{B.4}$$

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 $K_v^{\text{energydemand,drive}}$.

$$q_{v,t}^{\text{drive}} \le bin_{i,v,t} \cdot s_{v,t} \cdot K_v^{\text{energydemand,drive}} \quad \forall v \in \mathcal{V} \tag{B.5}$$

$$q_{v,t}^{\text{charge}} \le (1 - bin_{i,v,t}) \cdot P_{max}^{\text{charge}} \quad \forall v \in \mathcal{V} \tag{B.6}$$

B.2. 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 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 technology factor $K^{\text{wash,recovery}}$.

$$q_t^{\text{wash,recovery}} = Share^{\text{sewage}} \cdot V^{\text{wash}} \cdot K^{\text{wash,recovery}} \cdot \Delta T \tag{B.9}$$

B.3. 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.

$$q_t^{\text{industryexhaust}} \le P_{max}^{\text{industryexhaust}} \cdot \Delta t \tag{B.11}$$

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).

$$3\,\text{kWh} \le q_t^{\text{industryexhaust}} \le 6\,\text{kWh} \tag{B.12}$$

B.4. Water sale

Water sale is implemented to ensure that a certain portion of the sewage, referred to as greywater (Maldet, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer, 2022), 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.

$$v_{LSC,t}^{\text{greywater,sold}} \le Share^{\text{greywater}} \cdot v_{LSC,t}^{\text{sewage}} \tag{B.13}$$

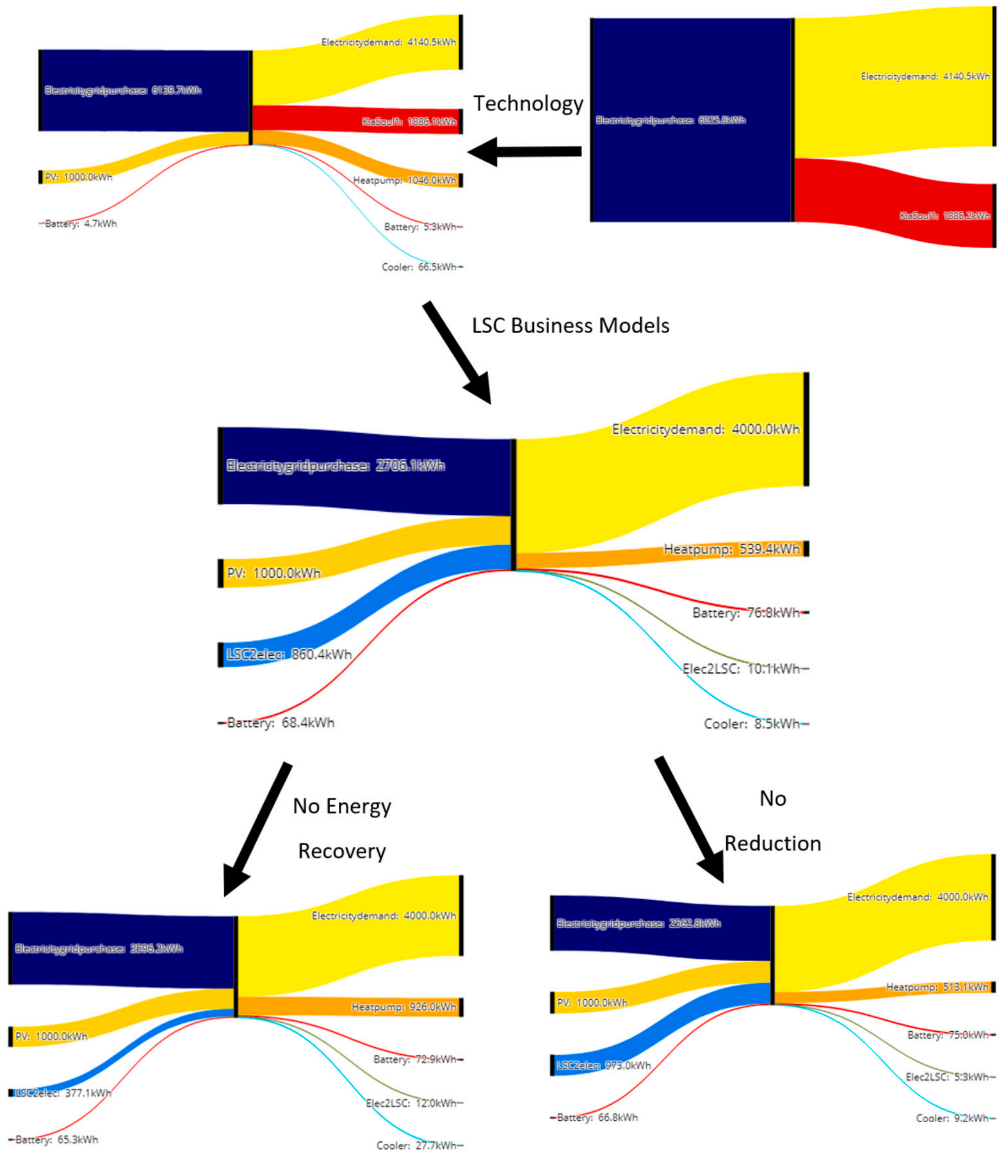

Fig. C.17. Model validation.

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.

$$v^{\text{sewage}}_{\text{LSC,t}} = v^{\text{greywater,sold}}_{LSC,t} + v^{\text{greywater,treated}}_{LSC,t} \tag{B.14}$$

For the greywater sale, predefined prices are assumed according to the conventional pipeline purchase price $\Pi^{\text{pipeline}}_{Water}$. 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.

$$rev^{\text{greywater,sold}}_{LSC,t} = v^{\text{greywater,sold}}_{LSC,t} \cdot F^{\text{watermarket}} \cdot \Pi^{\text{pipeline}}_{Water} \tag{B.15}$$

Appendix C. Model validation

The model validation process is described in this section. The initial model validation investigations were conducted in the course of the basic RUTIS model development, which is presented in (Maldet, Schwabeneder, Lettner, Loschan, Corinaldesi and Auer, 2022). Extensions to the model include the introduction of the LSC operator, LSC business models, and an extension to multiple consumers. These additional functionalities needed to be validated within the model development for the LSC analyses.

The case study presented in Fig. 5 is set up in a way, that technologies and services are gradually introduced to the LSC. With these introduced technologies and services, an improved in LSC performance can be expected. The service omission analyses in particular provide different results that can be checked for model validation. The quantitative and detailed impact are part of the result analyses, while the expected behavior and cross-check are part of the model validation. Validation and research are strongly related. However, a detail that should be considered is that the model behavior can only be slightly predicted. Only non-expected model behavior without reasonable explanation would indicate a model error. Fig. C.17 shows the model validation for the electricity sector of Consumer 1 in the LSC. The electricity grid consumption increases with the technology introduction. The grid consumption increase is valid, because other technologies such as heat pumps and electric coolers are operated. Introducing LSC business models decreases the electricity demand, because the washing machine operation is assigned to the LSC operator. The same accounts for electric vehicles. Therefore, the overall reduction of electricity assigned to Consumer 1 is validated. Electricity trading was performed as implemented, and we checked that if no circular trading flows took

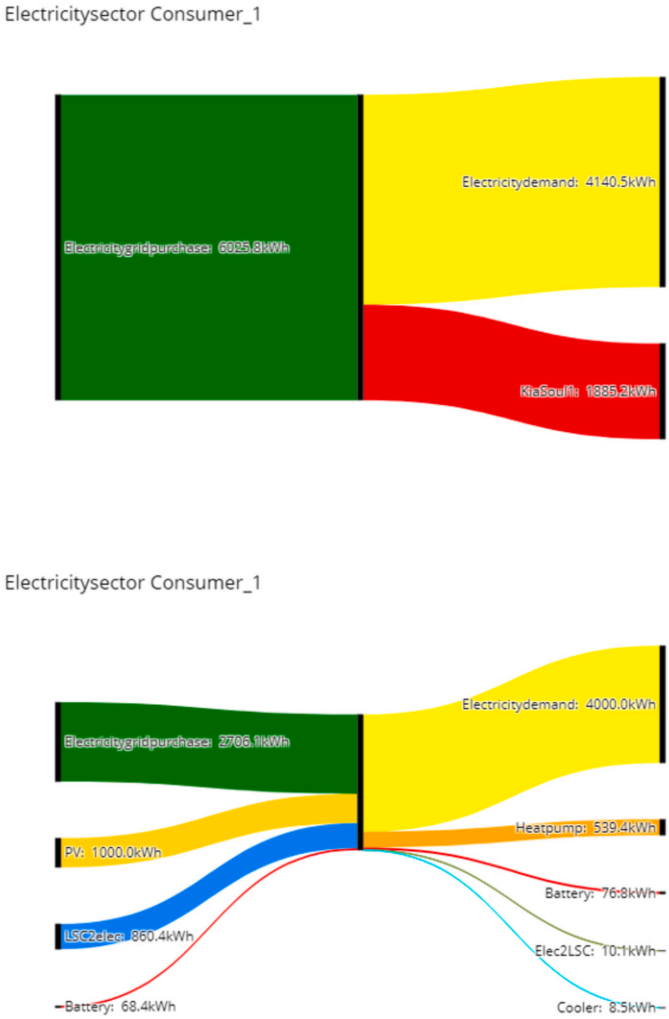

Fig. D.18. Electricity impact LSC.

place. The omission of energy recovery leads to an expected increase in electricity grid consumption and a decrease in LSC purchase. Moreover, waste and water reduction omission decrease the electricity grid consumption as increased resources are treated for energy recovery. In summary, the model could be validated because no inexplicable behavior occurred in the analyses.

Appendix D. LSC sector impact

The results for LSC business models from Section 4.1 are presented in this section. The impact of LSC models on consumers' electricity consumption is presented in Fig. D.18, while the LSC electricity sector is shown in Fig. D.19.

Fig. D.20 presents the input and output flows for an LSC member and the LSC operator in the heat sector.

Heat can be provided by several options, such as energy recovery and heat pumps. The sale of heat to consumers is conducted, whereas the sale of heat from consumers to the LSC is not conducted. This approach is similar to cooling, as presented in Fig. D.21.

As shown by the water flow diagram in Fig. D.22, all available water purchase options are used apart from excess purchases. Water reduction flexibility is implemented to enable consumers to save costs by the water pool.

As outlined in the waste and sludge treatment sankey diagrams in Fig. D.23, all waste and sludge is treated for energy recovery without restrictions. The alternative value in waste and sludge is negative, as it

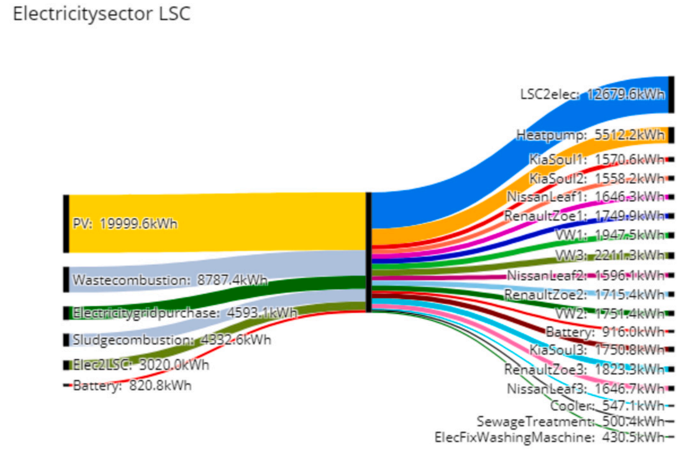

Fig. D.19. LSC electricity sector.

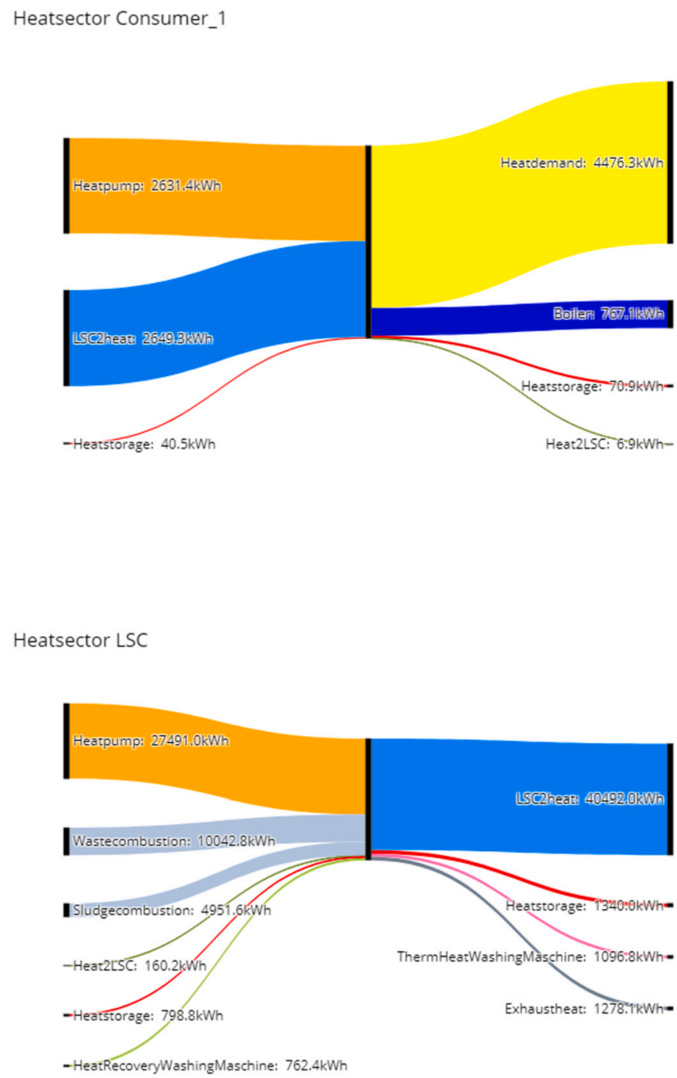

Fig. D.20. Heat flows.

only generates disposal costs. Therefore, treatment is always the preferable option.

Finally, the emission diagrams in Fig. D.24 present multiple emission sources. For consumer emissions, the primary source is the electricity grid due to the non-emission-free electricity mix. Emissions of waste and sludge transport to treatment plants are not negligible. LSC

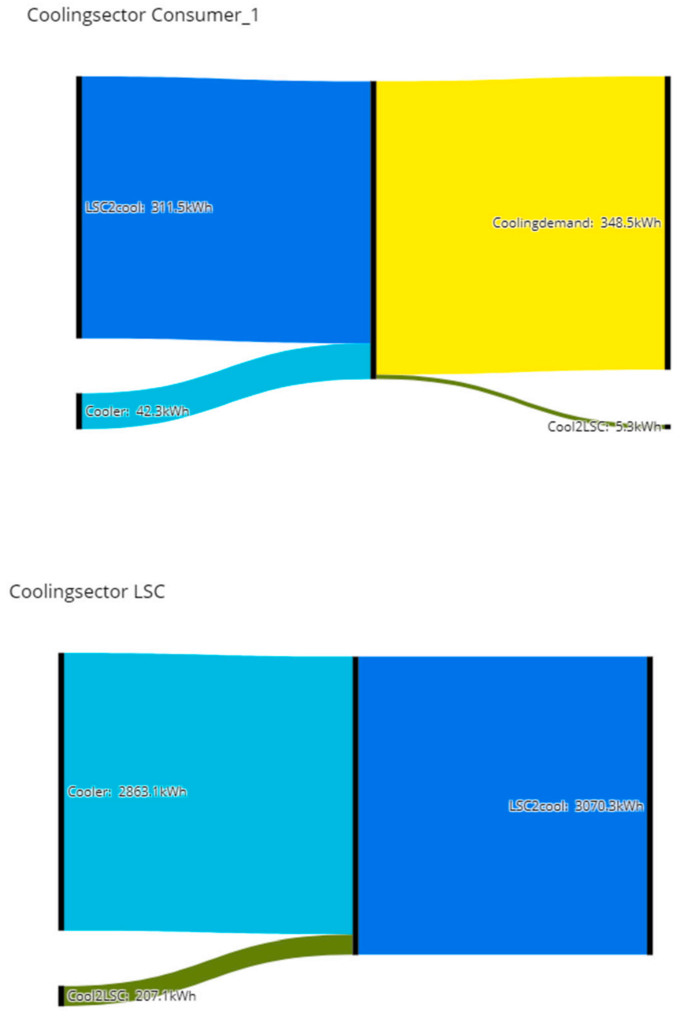

Fig. D.21. Cooling flows.

Fig. D.22. Water flows.

emissions emerge mainly from combustion technologies. However, the consumers' emissions continue to have a major share of the total emissions.

References

Abdalla, A., Mohamed, S., Bucking, S., Cotton, J.S., 2021. Modeling of thermal energy sharing in integrated energy communities with micro-thermal networks. Energy Build. 248, 111170.

Aguiñaga, E., Henriques, I., Scheel, C., Scheel, A., 2018. Building resilience: a self-sustainable community approach to the triple bottom line. J. Clean. Prod. 173, 186–196.

Aivazidou, E., 2022. Water management in agriculture and industry: challenges, trends, and opportunities. Sustainability 14.

Amulen, J., Kasedde, H., Serugunda, J., Lwanyaga, J.D., 2022. The potential of energy recovery from municipal solid waste in Kampala City, Uganda by incineration. Energy Convers. Manag. X 14, 100204.

Azarova, V., Cohen, J., Friedl, C., Reichl, J., 2019. Designing local renewable energy communities to increase social acceptance: evidence from a choice experiment in Austria, Germany, Italy, and Switzerland. Energy Policy 132, 1176–1183.

Babalola, S.O., Nel, J.J., Tshigo, V., Daramola, M.O., Iwarere, S.A., 2022. An integrated waste-to-energy approach: a resilient energy system design for sustainable communities. Energy Convers. Manag. 258, 115551.

Backe, S., Korpås, M., Tomasgard, A., 2021. Heat and electric vehicle flexibility in the European power system: a case study of Norwegian energy communities. Int. J. Electr. Power Energy Syst. 125, 106479.

Bartolini, A., Carducci, F., Muñoz, C.B., Comodi, G., 2020. Energy storage and multi energy systems in local energy communities with high renewable energy penetration. Renew. Energy 159, 595–609.

Baños, R., Manzano-Agugliaro, F., Montoya, F.G., Gil, C., Alcayde, A., Gómez, J., 2011. Optimization methods applied to renewable and sustainable energy: a review. Renew. Sustain. Energy Rev. 15, 1753–1766.

Beaumias, O., Briand, A., Millock, K., Nauges, C., 2009. Residential water use: water conservation and water quality. http://www.oecd.org/env/consumption-innovation/43181277.pdf.

Broska, L.H., 2021. It's all about community: on the interplay of social capital, social needs, and environmental concern in sustainable community action. Energy Res. Soc. Sci. 79, 102165.

Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2021. Informationsblatt CO2-Faktoren. https://www.bafa.de/SharedDocs/Downloads/DE/Energie/eew_infoblatt_co2_faktoren_2021.pdf?__blob=publicationFile&v=5.

Campos, J.L., Valenzuela-Heredia, D., Pedrouso, A., del Río, A.V., Belmonte, M., Mosquera-Corral, A., 2016. Greenhouse gases emissions from wastewater treatment plants: minimization, treatment, and prevention. J. Chem. 2016, 3796352.

Chen, Y.C., Kuo, J., 2016. Potential of greenhouse gas emissions from sewage sludge management: a case study of Taiwan. J. Clean. Prod. 129, 196–201.

Cielo, A., Margiaria, P., Lazzeroni, P., Mariuzzo, I., Repetto, M., 2021. Renewable Energy Communities business models under the 2020 Italian regulation. J. Clean. Prod. 316, 128217.

Ding, A., Zhang, R., Ngo, H.H., He, X., Ma, J., Nan, J., Li, G., 2021. Life cycle assessment of sewage sludge treatment and disposal based on nutrient and energy recovery: a review. Sci. Total Environ. 769, 144451.

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, 2018.

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, 2019.

Dóci, G., Vasileiadou, E., Petersen, A.C., 2015. Exploring the transition potential of renewable energy communities. Futures 66, 85–95.

Egan, J., 2004. The Egan Review: Skills for Sustainable Communities. RIBA Enterprises.

EuropeanCommission, 2020. Questions and answers: an EU strategy for energy system integration. https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_1258. (Accessed 21 October 2021).

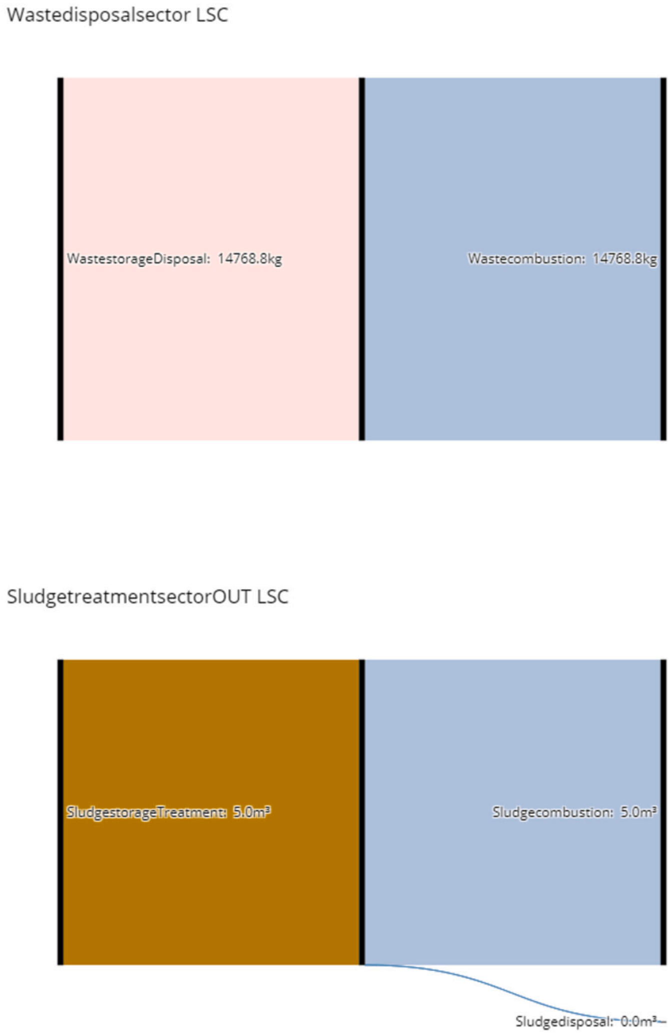

Fig. D.23. Waste and sludge flows.

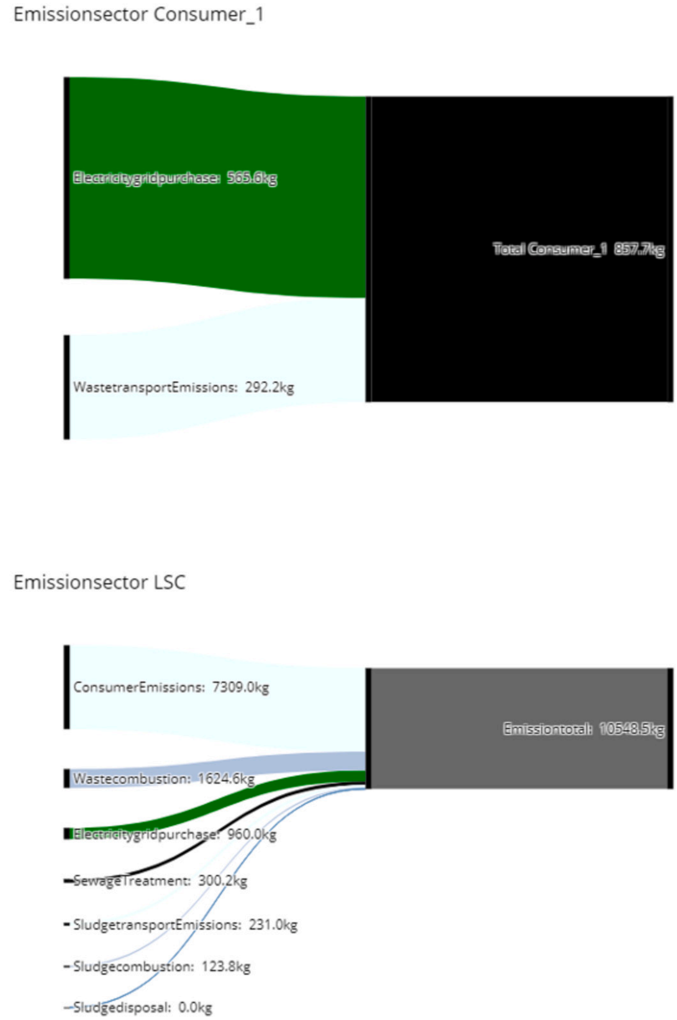

Fig. D.24. Emission sources.

European Commission, 2022. In focus: solar energy – harnessing the power of the sun. https://ec.europa.eu/info/news/focus-solar-energy-harnessing-power-sun-2022-sep-05_en. (Accessed 6 October 2022).

Fouladvand, J., Ghorbani, A., Mouter, N., Herder, P., 2022. Analysing community-based initiatives for heating and cooling: a systematic and critical review. Energy Res. Soc. Sci. 88, 102507.

Franzoi, N., Prada, A., Verones, S., Baggio, P., 2021. Enhancing PV self-consumption through energy communities in heating-dominated climates. Energies 14.

Gallego-Castillo, C., Heleno, M., Victoria, M., 2021. Self-consumption for energy communities in Spain: a regional analysis under the new legal framework. Energy Policy 150, 112144.

Geissdoerfer, M., Morioka, S.N., de Carvalho, M.M., Evans, S., 2018. Business models and supply chains for the circular economy. J. Clean. Prod. 190, 712–721.

Good, N., Mancarella, P., 2019. Flexibility in multi-energy communities with electrical and thermal storage: a stochastic, robust approach for multi-service demand response. IEEE Trans. Smart Grid 10, 503–513.

Green Energy Lab, 2021. Hybrid LSC. https://greenenergylab.at/projects/hybrid-lsc/. (Accessed 2 July 2021).

Gui, E.M., MacGill, I., 2018. Typology of future clean energy communities: an exploratory structure, opportunities, and challenges. Energy Res. Soc. Sci. 35, 94–107.

Gungor, B., Dincer, I., 2021. Development of a sustainable community with an integrated renewable and waste to energy system for multiple useful outputs. J. Clean. Prod. 312, 127704.

Haas, R., Nakicenovic, N., Ajanovic, A., Faber, T., Kranzl, L., Müller, A., Resch, G., 2008. Towards sustainability of energy systems: a primer on how to apply the concept of energy services to identify necessary trends and policies. Energy Policy 36, 4012–4021.

Hahnel, U.J., Herberz, M., Pena-Bello, A., Parra, D., Brosch, T., 2020. Becoming prosumer: revealing trading preferences and decision-making strategies in peer-to-peer energy communities. Energy Policy 137, 111098.

Hasan, A., Dincer, I., 2019. Development of an integrated wind and PV system for ammonia and power production for a sustainable community. J. Clean. Prod. 231, 1515–1525.

Heyes, G., Sharmina, M., Mendoza, J.M.F., Gallego-Schmid, A., Azapagic, A., 2018. Developing and implementing circular economy business models in service-oriented technology companies. J. Clean. Prod. 177, 621–632.

Hilpert, S., Kaldemeyer, C., Krien, U., Günther, S., Wingenbach, C., Plessmann, G., 2018. The Open Energy Modelling Framework (oemof) - a new approach to facilitate open science in energy system modelling. Energy Strategy Rev. 22, 16–25.

Hippel, D.V., Suzuki, T., Williams, J.H., Savage, T., Hayes, P., 2011. Energy security and sustainability in Northeast Asia. Energy Policy 39, 6719–6730.

Hoicka, C.E., Lowitzsch, J., Brisbois, M.C., Kumar, A., Camargo, L.R., 2021. Implementing a just renewable energy transition: policy advice for transposing the new European rules for renewable energy communities. Energy Policy 156, 112435.

IEA Bioenergy, 2013. Municipal Solid Waste and its Role in Sustainability.

Institute for Sustainable Communities, 2022. What is a sustainable community? https://sustain.org/about/what-is-a-sustainable-community/. (Accessed 22 September 2022).

International Energy Agency, 2021. Global energy review: CO2 emissions in 2021. https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2. (Accessed 21 October 2021).

Jedamzik, M., 2022. Wasserverbrauch im 4-Personen-Haushalt. https://www.co2online.de/energie-sparen/heizenergie-sparen/warmwasser/wasserverbrauch-4-personen-haushalt/#c157123. (Accessed 4 October 2022).

Khan, S., Anjum, R., Raza, S.T., Bazai, N.A., Ihtisham, M., 2022. Technologies for municipal solid waste management: current status, challenges, and future perspectives. Chemosphere 288, 132403.

Landesamt für Umwelt Brandenburg, 2018. CO2-Emissionsfaktoren nach Energieträgern. https://lfu.brandenburg.de/cms/media.php/lbm1.a.3310.de/emissionsfaktoren_co2_2017.pdf. (Accessed 5 October 2022).

Lewandowski, M., 2016. Designing the business models for circular economy—towards the conceptual framework. Sustainability 8.

Liu, Z., Fan, G., Sun, D., Wu, D., Guo, J., Zhang, S., Yang, X., Lin, X., Ai, L., 2022. A novel distributed energy system combining hybrid energy storage and a multi-objective optimization method for nearly zero-energy communities and buildings. Energy 239, 122577.

Lopez, V., Teufel, J., Gensch, C.-O., 2020. How a transformation towards sustainable community catering can succeed. Sustainability 12.

Lowitzsch, J., Hoicka, C.E., van Tulder, F.J., 2020. Renewable energy communities under the 2019 European Clean Energy Package – governance model for the energy clusters of the future? Renew. Sustain. Energy Rev. 122, 109489.

Lu, Y., Geng, Y., Liu, Z., Cote, R., Yu, X., 2017. Measuring sustainability at the community level: an overview of China's indicator system on National Demonstration Sustainable Communities. J. Clean. Prod. 143, 326–335.

Makropoulos, C.K., Butler, D., 2010. Distributed water infrastructure for sustainable communities. Water Resour. Manag. 24, 2795–2816.

Maldet, M., 2022. RUTIS. https://gitlab.com/team-ensys/projects/maldet_energysystemmodel. (Accessed 3 October 2022).

Maldet, M., Revheim, F.H., Schwabeneder, D., Lettner, G., del Granado, P.C., Saif, A., Löschenbrand, M., Khadem, S., 2022. Trends in local electricity market design: regulatory barriers and the role of grid tariffs. J. Clean. Prod. 358, 131805.

Maldet, M., Schwabeneder, D., Lettner, G., Loschan, C., Corinaldesi, C., Auer, H., 2022. Beyond traditional energy sector coupling: conserving and efficient use of local resources. Sustainability 14.

Mihajlov, A., 2010. Opportunities and challenges for a sustainable energy policy in SE Europe: SE European Energy Community Treaty. Renew. Sustain. Energy Rev. 14, 872–875.

Morris, A., Zuo, J., Wang, Y., Wang, J., 2018. Readiness for sustainable community: a case study of Green Star Communities. J. Clean. Prod. 173, 308–317.

Namany, S., Al-Ansari, T., Govindan, R., 2019. Sustainable energy, water and food nexus systems: a focused review of decision-making tools for efficient resource management and governance. J. Clean. Prod. 225, 610–626.

Nogueira, C., Marques, J.F., Pinto, H., 2022. Intentional sustainable communities and sustainable development goals: from micro-scale implementation to scalability of innovative practices. J. Environ. Plan. Manag., 1–22. https://doi.org/10.1080/09640568.2022.2106553.

Orehounig, K., Mavromatidis, G., Evins, R., Dorer, V., Carmeliet, J., 2014. Towards an energy sustainable community: an energy system analysis for a village in Switzerland. Energy Build. 84, 277–286.

Otaki, Y., Ueda, K., Sakura, O., 2017. Effects of feedback about community water consumption on residential water conservation. J. Clean. Prod. 143, 719–730.

Ozturk, M., Dincer, I., 2021. A new geothermally driven combined plant with energy storage option for six useful outputs in a sustainable community. Sustain. Energy Technol. Assessments 45, 101180.

Papatsounis, A.G., Botsaris, P.N., Katsavounis, S., 2022. Thermal/cooling energy on local energy communities: a critical review. Energies 15.

Peccia, J., Westerhoff, P., 2015. We should expect more out of our sewage sludge. Environ. Sci. Technol. 49, 8271–8276. https://doi.org/10.1021/acs.est.5b01931.

Rae, C., Bradley, F., 2012. Energy autonomy in sustainable communities—a review of key issues. Renew. Sustain. Energy Rev. 16, 6497–6506.

Ranta, V., Aarikka-Stenroos, L., Mäkinen, S.J., 2018. Creating value in the circular economy: a structured multiple-case analysis of business models. J. Clean. Prod. 201, 988–1000.

Reis, I.F., Gonçalves, I., Lopes, M.A., Antunes, C.H., 2021. Business models for energy communities: a review of key issues and trends. Renew. Sustain. Energy Rev. 144, 111013.

Ritchie, N., Smith, C., 2009. Comparison of greenhouse gas emissions from waste-to-energy facilities and the Vancouver landfill. http://pentz.com/NoIncinerator/greenhouse%20Emmissions.pdf.

Rizos, V., Behrens, A., der Gaast, W., Hofman, E., Ioannou, A., Kafyeke, T., Flamos, A., Rinaldi, R., Papadelis, S., Hirschnitz-Garbers, M., Topi, C., 2016. Implementation of circular economy business models by small and medium-sized enterprises (SMEs): barriers and enablers. Sustainability 8.

Romero-Rubio, C., de Andrés Díaz, J.R., 2015. Sustainable energy communities: a study contrasting Spain and Germany. Energy Policy 85, 397–409.

Rosenkranz, A., 2020. Der durchschnittliche Energiebedarf im Haus. 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. (Accessed 4 October 2022).

Santillan, M.R., Syn, J.W., Shandiz, S.C., Huang, Y., de Lacerda, M., Rismanchi, B., 2022. A technology assessment approach for achieving sustainable communities: an energy master plan for a new urban development. Appl. Sci. 12.

Sapkota, M., Arora, M., Malano, H., Moglia, M., Sharma, A., George, B., Pamminger, F., 2015. An overview of hybrid water supply systems in the context of urban water management: challenges and opportunities. Water 7, 153–174.

Schodl, B., 2019. Statusbericht zu den CO2 Emissionen neu zugelassener Pkw in Österreich im Jahr 2018. https://www.bmk.gv.at/dam/jcr:9c5c0fba-a8b9-41dc-9f5e-6f839e9cb68f/CO2_Monitoring_PKW_2018.pdf. (Accessed 21 July 2022).

Schoor, T.V.D., Scholtens, B., 2015. Power to the people: local community initiatives and the transition to sustainable energy. Renew. Sustain. Energy Rev. 43, 666–675.

Schwabeneder, D., Corinaldesi, C., Lettner, G., Auer, H., 2021. Business cases of aggregated flexibilities in multiple electricity markets in a European market design. Energy Convers. Manag. 230, 113783.

Schweizer-Ries, P., 2008. Energy sustainable communities: environmental psychological investigations. Energy Policy 36, 4126–4135.

Seyranian, V., Sinatra, G.M., Polikoff, M.S., 2015. Comparing communication strategies for reducing residential water consumption. J. Environ. Psychol. 41, 81–90.

Si, H., Duan, X., Zhang, W., Su, Y., Wu, G., 2022. Are you a water saver? Discovering people's water-saving intention by extending the theory of planned behavior. J. Environ. Manag. 311, 114848.

Silvestre, M.L.D., Ippolito, M.G., Sanseverino, E.R., Sciumè, G., Vasile, A., 2021. Energy self-consumers and renewable energy communities in Italy: new actors of the electric power systems. Renew. Sustain. Energy Rev. 151, 111565.

Singh, V., Phuleria, H.C., Chandel, M.K., 2020. Estimation of energy recovery potential of sewage sludge in India: waste to watt approach. J. Clean. Prod. 276, 122538.

Statista, 2022a. Aufkommen von Haushaltsabfällen je Einwohner in Deutschland in den Jahren 2004 bis 2020. https://de.statista.com/statistik/daten/studie/161228/umfrage/haushaltsabfaelle-je-einwohner-seit-dem-jahr-2003/. (Accessed 4 October 2022).

Statista, 2022b. 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? https://de.statista.com/statistik/daten/studie/1304250/umfrage/umfrage-zur-persoenlichen-einstellung-zum-recycling-in-oesterreich/. (Accessed 1 May 2022).

Tomić, T., Schneider, D.R., 2022. "Closing two loops"—the importance of energy recovery in the "closing the loop" approach. In: Circular Economy and Sustainability: Volume 1: Management and Policy, pp. 433–455.

Tostado-Véliz, M., Kamel, S., Hasanien, H.M., Turky, R.A., Jurado, F., 2022. Optimal energy management of cooperative energy communities considering flexible demand, storage and vehicle-to-grid under uncertainties. Sustain. Cities Soc. 84, 104019.

Umwelt, Energie, Mobilität, Innovation und Technologie Bundesministerium für Klimaschutz, 2022. Das Übereinkommen von Paris. https://www.oesterreich.gv.at/themen/bauen_wohnen_und_umwelt/klimaschutz/1/Seite.1000325.html. (Accessed 22 September 2022).

United Nations, 2021. Causes and effects of climate change. https://www.un.org/en/climatechange/science/causes-effects-climate-change. (Accessed 21 October 2021).

United Nations, 2022. Do you know all 17 SDGs? https://sdgs.un.org/goals. (Accessed 22 September 2022).

Urbinati, A., Chiaroni, D., Chiesa, V., 2017. Towards a new taxonomy of circular economy business models. J. Clean. Prod. 168, 487–498.

Vallecha, H., Bhattacharjee, D., Osiri, J.K., Bhola, P., 2021. Evaluation of barriers and enablers through integrative multicriteria decision mapping: developing sustainable community energy in Indian context. Renew. Sustain. Energy Rev. 138, 110565.

Verein GeWoZu, 2020. Gemeinschaftlich Wohnen Die Zukunft. https://gewozu.at/. (Accessed 4 October 2022).

Vogel, B., 2018. Wenn Kühlen wichtiger wird als Heizen. https://www.gebaeudetechnik.ch/waerme-kaelte/kaeltetechnik/kaelteanlagen/wenn-kuehlen-wichtiger-wird-als-heizen/. (Accessed 4 October 2022).

Vu, M.T., Nguyen, L.N., Zdarta, J., Mohammed, J.A.H., Pathak, N., Nghiem, L.D., 2022. Chapter 1 - Wastewater to R3 – resource recovery, recycling, and reuse efficiency in urban wastewater treatment plants. Elsevier.

Weißbach, A., 2022. Stromverbrauch im Haushalt. https://www.co2online.de/energie-sparen/strom-sparen/strom-sparen-stromspartipps/stromverbrauch-im-haushalt/#:~:text=F%C3%BCr%20Deutschland%20gilt%3A%202%20Personen,%20Euro. (Accessed 4 October 2022).

Xia, B., Chen, Q., Skitmore, M., Zuo, J., Li, M., 2015. Comparison of sustainable community rating tools in Australia. J. Clean. Prod. 109, 84–91.

Yaman, C., Anil, I., Alagha, O., 2020. Potential for greenhouse gas reduction and energy recovery from MSW through different waste management technologies. J. Clean. Prod. 264, 121432.

Young, J., Brans, M., 2017. Analysis of factors affecting a shift in a local energy system towards 100% renewable energy community. J. Clean. Prod. 169, 117–124.

Zaharioiu, A.M., Bucura, F., Ionete, R.E., Marin, F., Constantinescu, M., Oancea, S., 2021. Opportunities regarding the use of technologies of energy recovery from sewage sludge. SN Appl. Sci. 3, 775.

Zsigraiová, Z., Tavares, G., Semiao, V., de Graça Carvalho, M., 2009. Integrated waste-to-energy conversion and waste transportation within island communities. Energy 34, 623–635.