Integration of Sustainable Water- and Waste Management into Energy Communities

Matthias Maldet[a,*], Georg Lettner[a], Daniel Schwabeneder[a]

[a] *TU Wien*
Institute of Energy Systems and Electrical Drives
Energy Economics Group (EEG)
Gußhausstraße 25-29/E370-3, A-1040 Vienna

Abstract

For the decarbonization of the energy system, a holistic view considering all energy sectors is mandatory. The interaction between energy sectors in sector coupling concepts and the extension of the idea to a joint use and generation by prosumers together with consumers within energy communities can also open up new possibilities. Waste and water as energy sectors have been barely considered in these conceptions yet. In this paper, a literature review on existing waste and water management concepts and their contribution to a sustainable treatment of the resources is performed, with additional consideration of energy recovery opportunities. Based on the findings, a possible integration of waste and water into sector coupling models as well as a joint usage of both in energy communities are investigated. Building up upon this, a sector coupling model conception with consideration of waste and water is developed and a possible application in a theoretical use case is described. The analyses show that waste and water have a lot of potential for more sustainability in their treatment and disposal chains, whereas energy recovery processes can further increase the overall sustainability and make it possible to integrate waste and water into sector coupling models. Furthermore, energy communities can be fundamental for increasing the efficiency of waste and water management processes, while also using recovered energy of waste and water by operating sector coupling technologies within the community. Future investigations on energy systems must therefore include waste and water as energy sectors to exploit the full potential of sector coupling and energy communities.

Keywords: Waste and Water Management, Energy Recovery, Sustainability, Energy System Decarbonization, Sector Coupling, Energy Community, Holistic Energy System

---

*Corresponding author. Phone: +43-(0)1-58801-370365
Email address: maldet@eeg.tuwien.ac.at (Matthias Maldet)

Abbreviations

CEC	Citizen Energy Community
CHP	Combined Heat and Power
$\mathbf{CO_2}$	Carbon Dioxide
EC	Energy Community
EU	European Union
GHG	Greenhouse Gas
NGO	Non Governmental Organisations
PV	Photovoltaic
P2G	Power to Gas
P2H	Power to Heat
REC	Renewable Energy Community
SC	Sector Coupling
SSL	Source Separation Level
V2G	Vehicle to Grid

Nomenclature

$\eta^{conversion}$	Conversion Factor/Efficiency
$C^{process}$	Process Operation Costs
$C^{purchase}$	Energy Purchase Costs
C^{total}	Total Costs in Use Case
i	Index Input Energy Sector for Conversion Technology
j	Index Output Energy Sector for Conversion Technology
k	Index for Conversion Technology
$M_t^{waste,Acccruing}$	Amount of accruing Waste in kg
$m_t^{waste,waste2Gas}$	Waste provided for Anaerobic Digestion in kg
$m_t^{waste,WasteComb}$	Amount of combusted Waste in kg
$m_t^{waste,WasteDisposal}$	Amount of disposed Waste in kg
$Q_t^{el,Demand}$	Electrical Energy Demand in kWh
$q_t^{el,FeedIn}$	Electrical Energy fed into the Grid in kWh
$q_t^{el,GridPurchase}$	Electrical Energy purchased from the Grid in kWh
$q_t^{el,groundwaterwell}$	Electrical Energy Demand for Groundwaterwell in kWh
$q_t^{el,HP}$	Energy from Electricity Sector to Heat Pump in kWh
$Q_t^{el,PV}$	Electrical Energy generated from the Household Power Plant in kWh
$q_t^{el,sludgeCombustion}$	Electrical Energy gained from Sludge Combustion in kWh
$q_t^{el,wasteComb}$	Electrical Energy gained from Waste Combustion in kWh
$q_t^{gas,AD}$	Gas generated by Anaerobic Digestion of Sewage Sludge in kWh
$Q_t^{gas,Demand}$	Gas Demand in kWh
$q_t^{gas,GasBoil}$	Gas combusted in the Gas Boiler in kWh

$q_t^{gas,GridPurchase}$	Gas purchased from the Grid in kWh
$q_t^{gas,Waste2Gas}$	Gas generated by Anaerobic Digestion of Waste in kWh
$Q_t^{heat,Demand}$	Thermal Energy Demand in kWh
$q_t^{heat,GasBoil}$	Thermal Energy provided by the Gas Boiler in kWh
$q_t^{heat,GridPurchase}$	Heat purchased from the District Heat in kWh
$q_t^{heat,HP}$	Heat provided by the Heat Pump in kWh
$q_t^{heat,sewageTreatment}$	Exhaust Heat from Sewage Treatment in kWh
$q_t^{heat,sludgeCombustion}$	Heat provided by Sludge Combustion in kWh
$q_t^{heat,wasteComb}$	Heat provided by Waste Combustion in kWh
$V_t^{water,Demand}$	Water Demand in m^3
$v_t^{water,groundwaterwell}$	Water provided by the groundwaterwell in m^3
$v_t^{water,Pipeline}$	Water purchased from public Pipelines in m^3
$v_t^{water,waterRecovery}$	Recovered Water from Sewage Treatment in m^3
x_t	Input or Output Parameter for Conversion Technologies

1. Introduction

For reaching climate neutrality by 2050 and forming a sustainable society, it is required to reduce the Greenhouse Gas (GHG) emissions in all energy sectors, not only the electricity and heat sector, which are often the mainly considered energy services in this context. To achieve the emission reduction, an increasing use of renewable energy sources and the use of new fuels in all sectors are necessary, while preventing a sufficient security of supply. Therefore, future energy systems must be planned as a whole with a holistic view on the energy sectors and energy generation technologies in form of Sector Coupling (SC) concepts, rather than only considering each sector as separate entity. Such targets require the involvement of all stakeholders across the whole service and demand chain, so consumers must be given an active role in the transition of the energy system [1]. Active consumer integration leads to a decentralization of the energy generation plants. For a more efficient use of these decentral power plants, it is necessary to join forces with other producers and consumers is form of communities, rather than operating decentral renewable energy plants for self-consumption alone. Such a joint generation and use of energy can be achieved by the formation of an Energy Community (EC), which is defined on the regulatory level in [2] and [3]. Most investigations regarding ECs consider these concepts only for electricity sharing. To decarbonize the whole energy system, an extension to other energy sectors is mandatory. In this context, the heat and gas sectors are often referred to, as they offer additional storage technologies for electricity. Two sectors that are mostly neglected while investigating the energy system as a whole for SC are waste and water.

As environmental and health issues are emerging through waste treatment, and as water scarcity is a growing problem in the world, it is required to reduce both sources for a transition to a more sustainable society [4], [5]. For the transition it is mandatory to reduce consumption, and promote sustainable disposal and recycling concepts for waste and water. Therefore, well planned waste and water management concepts must be implemented, that also consider energy generation possibilities for waste and sewage in form of energy recovery. Waste and water management have been analyzed in different papers, for example in [6], [7] and [8]. Those papers have in common that the concepts are only applied in the respective sector. To get the maximum out of waste and water management, it is mandatory to include both into SC concepts and consider the joint use in ECs. The idea of integrating waste and water into SC models, which might be applied within ECs, is presented in figure 1. Thereby management concepts for waste and water must be implemented to guarantee an efficient use of both energy sectors.

To give an overview on the integration of waste and water into SC concepts, this paper is structured as follows. In the beginning, a literature review on existing waste and water management concepts and their possible implementation is performed, where the major ideas and goals, as well as the contribution of these management concepts to sustainability are analyzed. Building up upon this, the following section focuses more on energy recovery processes for waste and wa-

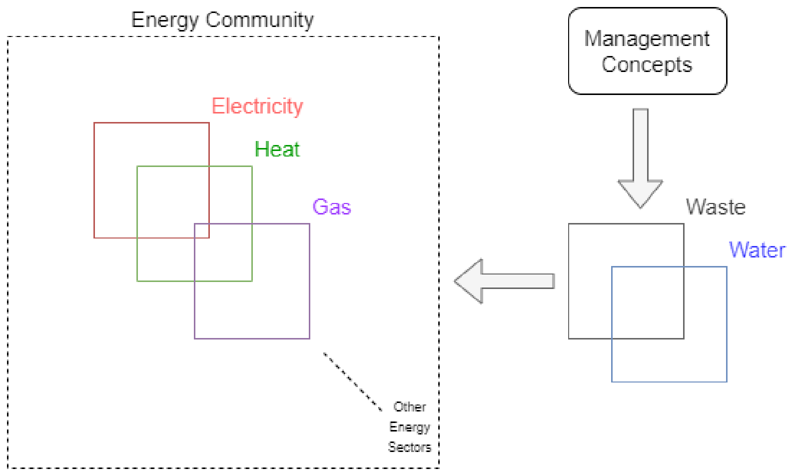

Figure 1: Extension of Sector Coupling by Waste and Water

ter, which are fundamental for the integration of these sectors into SC models. In this context, existing processes are examined based on their contribution to energy generation and regarding their influence on the environment. After the assessment of the management concepts and energy recovery processes, a more detailed discussion of waste and water integration into SC concepts and ECs is raised based on the previous findings. Thereby the ideas of SC and ECs are described, and building up upon that, possible implementation concepts for waste and water are analyzed. With all of the reviewed and analyzed aspects, a conception for a SC model including waste and water is developed for further investigations concerning this topic and is described in the final section. The fully developed model should work as a tool for the investigation of issues regarding implementation of waste and water into SC and ECs. Potential model implementation barriers in reality as well as a possible application of the model in a theoretical use case are described for a further understanding of the developed model. All the covered topics result in the following major contributions of the paper.

- **Management Concepts:** Provision of an overview on waste and water management concepts, as well as on energy recovery processes.
- **Holistic View on the Energy System:** Analysis on the integration of waste and water into SC and EC concepts.
- **Model Concept Development:** Modelling a concept for SC including waste and water for investigation of future research questions.

All the sections give an overview about the role of waste and water in the transition to a sustainable society.

2. Management Concepts

Waste and sewage are unavoidable outcomes that arise as by-products of an actual usable good. For a sustainable treatment of the waste, corresponding management concepts are necessary. These concepts should decrease the negative environmental impacts of the waste products, or even generate gains in form of energy utilisation of these products. Management concepts for both by-products have been investigated before in different papers, which makes it possible to generate experience from these studies.

2.1. Waste Management

Waste Classification

For waste management, the general idea and the implementation in form of waste reduction, separation and recycling are investigated. These implementation tools are essential for a sustainable treatment of the occurring waste. Such concepts are examined primary for municipal waste, but can also be applied to other waste sectors, whereby for the latter it is necessary to consider that toxic and non-recyclable wastes might occur more often and in higher amounts. In general, the waste sector classification distinguishes between municipal waste, ashes, animal waste, industrial waste, medical waste and hazardous waste. Municipal waste mainly consists of food scraps, packaging, miscellaneous inorganic waste and yard trimmings [9]. For medical waste and animal waste, special treatment is necessary as both can be infectious [10]. During the COVID-19 pandemic, the medical and plastic waste experienced a large increase as face-masks emerged as additional waste source according to [11] and [12], which underlines the increasing importance of waste separation. However, waste management includes the production, collection and transport, the processing as well as the disposal or reuse of waste. For waste production, which is defined as material entering the waste stream before treatment by [13], waste management is applied on the separation and internal collection. The internal gathered waste is then collected on a larger scale and transported to treatment plants, in which the kind of treatment is a form of waste management as well. In these treatment plants the waste is mostly burned or dumped on the countryside. Both treatment processes can be quoted as non-sustainable without further treatment. Thus it is essential to keep the amount of out coming waste on a low level which brings us back to waste reduction concepts [9]. A further goal of waste management is the recycling and re-introduction of occurring waste substances within the production cycles in form of re-usage of the materials as energy carriers [5]. Poorly implemented waste management practices can have a negative impact on the environment, like contamination of water and soil, as found by [14]. Similar results were found by [15], who examined a loss of the drinking water quality by groundwater near waste landfills. These results make it clear that waste management is not only essential for a sustainable society but also for the general health.

Main goals of waste management

Due to the health problems caused by poor waste management, regulatory frameworks are established to promote waste management [14]. To describe the idea of waste management more in detail, it is mandatory to specify waste management techniques. According to [9], a waste management system includes activities for handling, treating, disposing and recycling of waste. Thereby it is necessary to differ between combustible wastes that can be treated by incineration and gasification, and non-combustible waste, that must be further treated in landfills. As a special case, wood, plastics and organic materials are partly combustible [9]. For a further description, the different disposal options must be examined more precise, because they are an essential part of waste management. According to the investigations of [9], landfill disposal is the most cost effective option. In these landfills, the waste is dumped and degrading over time [16]. It has to be considered that the waste in landfills degrades very slowly, and that such landfills do not represent normal environmental conditions [5]. The problem thereby is, that the leachate causes treat to health and nature, which makes is necessary to implement further treatment of the landfill leachate [17]. A second option of waste disposal is the incineration of the emerging resources, that has the advantage that additionally to the waste disposal, energy can be recovered by the incineration process [18]. The waste incineration can be implemented on a local level by individuals or on a larger scale by the industry [9]. In these plants, a controlled combustion of the waste sources is carried out to generate heat and steam, which is used to empower a gas turbine [16]. An often mentioned critical aspect of waste incineration is the fact, that emissions are caused by the combustion, which makes it a rather non-sustainable treatment [9]. As a third option, anaerobic digestion and the corresponding generation of biogas is mentioned in existing papers. Thereby the organic material is converted directly into a gas mixture of methane and Carbon Dioxide (CO_2), that has a chemical composition close to natural gas. In such biogas plants, anaerobic conditions are provided to stimulate reactions [19]. The gas can then be used for engines, turbines and boilers and is considered as green gas[1]. Different yields between unlike biodegradable wastes underline the importance of waste separation once again [9], [16].

Waste Reduction

Before investigating waste separation methods, the waste reduction process is analysed more in detail as it is the first hierarchical step of options for reducing pollution in form of waste management according to [20]. Waste reduction is a concept that is poorly executed by residents of households, as a direct added value is not immediately apparent from it. Therefore, incentives for a more efficient implementation must be made. Tam and Tam [21] introduced a reward scheme to improve the lack of motivation and generate more experience factors for construction workers. In a stepwise incentive system, the costs saved on

[1] CO_2 neutrally produced gas

materials for construction were evaluated and rewarded to the workers as part of their salary. With 10 % to 15 % of the salary the waste-reduction dependent share was high enough to reduce the waste in the company by 23 %. A major impact on the waste reduction in this context was the raise of awareness in form of financial benefits. Incentives can also be set on the regulatory level, like in [22] where institutional pressure led companies to waste reduction investments. The waste reduction was influenced by the investment decisions. It was also examined that investments had a higher impact on pollution reduction than on cost reduction, which shows that incentives for waste reduction are an important aspect for a sufficient implementation of reduction concepts. Bandyopadhyay [20] mentioned that changes in processes are important for reduction of the overall waste. These modifications can be either made by changing the quality or the flow of internal sources or demands. It was also found that the reduction of the resource requirement leads to a reduction of the same amount in the waste generation. In summary it could be seen that waste reduction has a lot of potential which can help to achieve a more sustainable waste management.

Waste Separation and Recycling

Recycling is seen as the second step in the waste management hierarchy by [20]. For a proper recycling implementation, prior waste separation is an essential preliminary work. According to [23], recycle performance improvement can help to recover materials and save resources. The overall goal is to reduce the waste that is deposited in landfills. In the paper the legal authority is seen as a fundamental instance for the improvement of recycle performances, while public education is also considered as an important improvement factor. Social factors and the convenience of recycling are described as major aspects by [23] as well. The importance of a legal authority was mentioned by [24] in case of waste separation, as their study showed that policy instruments had a stronger impact on the separation behaviour than perceived costs. Xu et al. [25] extend this approach by further social aspects and mention Non Governmental Organisations (NGO) as possible mediator between residents and local authorities. The paper of Stoeva and Alriksson [26] focuses more on barriers for individuals, as they were sending out questionnaires to determine possible implementation barriers by applying the theory of planned behaviour, which is defined as the motivation and ability of behaviour in a specific situation [27]. In the course of these interviews they found that the recycling behaviour of private persons is heavily dependent on personal attitudes and on the satisfaction with local facilities. Similar to recycling, waste separation also depends on social aspects, which can be seen in the results of [28] where it is mentioned that the waste separation behaviour is strongly dependent on the location of the waste bins. This was also found by [29], as the waste separation rates increased with nearer distance to waste separation sites in the results of the study. Furthermore according to [30], the waste separation efficiency can be affected by regardless consumers, thus the results of this paper show that economic rewards lead to better waste separation behaviour than social influence. However, all these papers mentioned that waste separation and recycling behaviour are heavily dependent on individual aspects and on the convenience in which the processes can be carried out. The different studies in the considered papers showed, that economical and social incentives must be applied for an improvement of the behaviour of individuals, whereas the best strategy can not be exactly set. Both, separation and recycling, are fundamental processes for the relief of landfills and the efficient further processing of waste for energy recovery.

Waste Management Hierarchy

In figure 2 the hierarchy of waste management is summarized. Waste separation is considered as the second step in the hierarchy, as it must be done before recycling to guarantee an efficient recycling process. The emerging waste can then either be recycled, deposited in landfills, incinerated, digested for biogas production or used in other energy recovery processes.

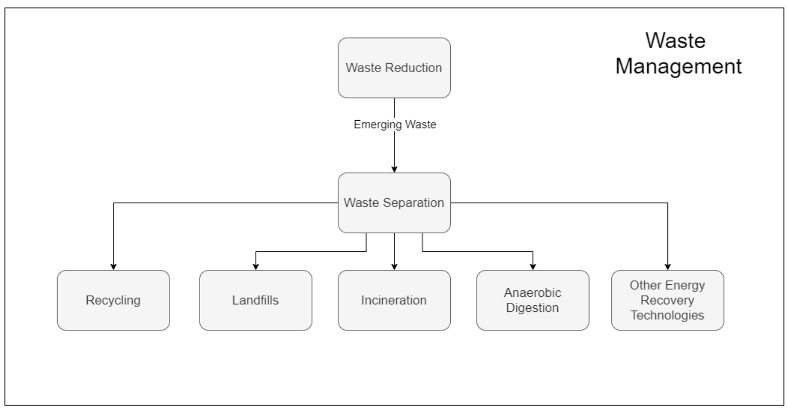

Figure 2: Waste Management Hierarchy

2.2. Water Management

Concept and Goals of Water Management

While waste management has been investigated in different papers before, water management is a barely considered concept and is mainly investigated in from of water reduction. Like for waste management, the goal of water management is to get the maximum out of the resource water, while consuming the minimum necessary amount of water. In that context, van der Brugge et al. [31] mentioned that water management cannot be seen as a single water problem due to the different forms of water like rainwater, groundwater, surface water and seawater for which different problems occur. According to [31], the main issues regarding water management are water demand and supply, water scarcity and sewage treatment. Environmental impacts like the sea level rise and alteration of the hydrological cycle are also mentioned by them. Furthermore water is considered as a resource with different functions in society by [31], as it has a function for navigation and agriculture, a function for drinking water supply in addition with other private uses and it has an ecological function for sustaining ecosystems. Therefore water management is a process across multiple utilities and must be done considering many different stakeholders. Water also has an economic value, which is expressed in form of a water price. Due to the water scarcity in different regions, the ecologic values expressed as ecosystem water regulation services are assigned a more important role than the economical values. The constraints for water management include the physical characteristics of water, as well as the regulation and water policies [31]. Water management is currently undergoing a transition process, which is a long-term structural change in society operations, respectively a shift between two equilibria [32]. In this transition process, water management has changed from a scientific style to a participatory style, which means that water management must also be done on the consumer level. Thus it is necessary to introduce water management concepts on the local level.

Water Reduction

One of the major aspects of water management is the reduction of the consumed water. Water reduction can be done on the municipal level in form of water savings for household processes. Thereby the usage of rainwater and reuse of greywater, which is water without drinking quality, can be major aspects, whereby the latter is seen as the most viable water reduction strategy by [33]. According to [34] the water price as well as the drought intensity can have a positive effect on water consumption reduction. Like waste reduction, water reduction is strongly dependent on individual routines. This is clarified by the increasing use of water during the COVID-19 pandemic, where the water consumption was rising up to 29 % during the lockdown periods [35]. The individual aspects of water consumption were investigated by [36], who carried out telephone interviews, whereby they found that pricing strategies are only useful for consumers that have an idea about the amount of water they are consuming. A further problem discovered by the interviews was, that most consumers are not aware about their possible high water consumption and thought other consumers would be the problem. All of the interviewed persons agreed on penalty charges for above average water consumption, as long as they were not affected by the payments. The results of this survey show that it is necessary to raise awareness on the private household sector regarding water consumption to achieve an effective water reduction in the long term. Smart meters[2] for water can help to raise awareness and give feedback on the water consumption [37]. Furthermore, the comparison with other consumers and with the average consumption of similar households could make the need for water reduction clearer for single consumers [38]. Water reduction must also be done in industrial processes and energy generation processes. A reduction of the electricity consumption leads directly to water consumption reductions. In California for example, an electricity consumption reduction of 16 % would make it possible

[2] intelligent measurement devices that allow monitoring of the consumption

to abandon hydro and nuclear power plants and reduce the total water consumption in the electric energy sector by 94 % [39][3]. This example shows that the different demand services interact strongly with each other. Furthermore, an increasing electric energy demand in the future can result to an additional water demand if the load is covered by water intensive power plants [40]. Regarding water consumption, wind power and Photovoltaic (PV) are the generation plants with the least water demand [41]. As can be seen, water reduction not only relies on the decreasing use of water, but also on electricity consumption reduction and generation with less water intensive power plants. Thus the water reduction concept is a wide-ranging topic.

Water Reuse

Water reuse is a kind of tool for water reduction. Thereby treated sewage can be used as a water resource. According to [42], the treated water could be used for purposes that do not need water with drinking water quality. The reuse of sewage can reduce pressure on conventional sources for covering the water demand. Between both water sources, the major differences are the more reliable supply of sewage in specific regions and the water quality, whereas the latter limits the possible usage of sewage. A great benefit from the reuse of water can be expected in the agricultural sector due to the high demand of water without drinking quality that is needed for field irrigation [43]. As the two water systems cannot be transported together in the same pipelines because of quality issues, separate pipelines would be necessary for the introduction of the concept [42]. However, for an efficient reuse of water, the one water concept, which defines water as a single resource, not distinguishing between drinking water and sewage due to the potential high quality of treated sewage in the future, must be implemented [44].

Water Management Hierarchy

Similar to waste management, the water management hierarchy is presented graphically in figure 3, whereas the reduction of water consumption is the first step, followed by water reuse, energy recovery from sewage water and non-recyclable sewage.

3. Energy Recovery

In the previous section, different management concepts for waste and water were introduced. As part of the concepts, energy recovery from the emerging waste and sewage was mentioned, which is now described more in detail.

3.1. Waste to Energy

The idea of waste to energy is the recovery of energy from the emerging waste. Thereby waste is removed and energy is recovered at the same time,

[3]not considering possible negative effects of hydro power abandonment

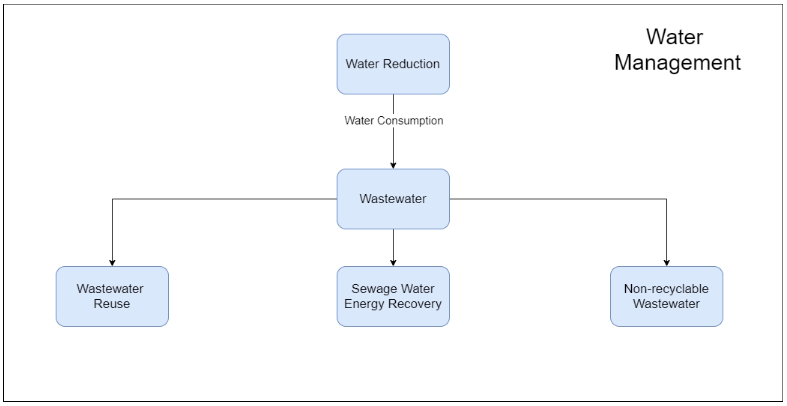

Figure 3: Water Management Hierarchy

so the point is to generate added value from waste disposal rather than just depositing waste on landfills. In [45] the advantages of energy recovery from waste are mentioned in form of electricity generation, new jobs, revenues and reducing the volume of waste in landfills in the long-term, while this could further help promoting clean environments and promote the transition to low-carbon cities [46]. As a performance indicator, the total recovered energy and the grade of emission were mentioned by [47]. Energy recovery from waste is implemented mainly in developed countries. To exploit the full potential, an implementation in developing countries is necessary as well. A barrier thereby is that information on energy recovery technologies is not shared for environmental interests, whereas the barrier is even higher in developing countries [48].

Further treatment of waste in energy recovery plants is dependent on the pre-treatment of the source. The source separation, whose efficiency is described with the Source Separation Level (SSL), is an important indicator for the total amount of material and energy recovered. According to [49], solid recovered fuel has the highest energy recovery potential. Thereby the external collection of waste is often considered, where it is distinguished between kerbside collection without stable street containers and drop-off collection with the possibility to drop off waste at any time of the week. Costs for drop-off collection are usually lower than costs for kerbside collection [50]. Not all papers agree on the importance of SSL, like [51] where it is stated that the performance of energy recovery systems is not significantly improving for increasing SSL. This is mainly dependent on the fact that the total output of energy recovery processes is not highly dependent on the SSL, while this does not account for all processes in waste management. As it is necessary to consider the whole waste management chain, waste separation must be considered as a relevant impact factor. The separation is important, as additionally to energy, material can be recovered. Residues of the recovered material can be used for energy recovery, which correlates to the goal of maximizing the yield of waste treatment [50]. However, costs occur for reaching higher SSL values and [50] examined that above a critical SSL of

50 %, the costs are rising. The same results specified that efficient material and energy recovery can only be achieved with SSLs above 75 %, which means that higher costs of separation must be accepted in order to save costs in the overall process of waste separation and energy recovery.

After pre-treatment, the waste is processed for energy recovery. In figure 2, incineration and anaerobic digestion have already been presented as possible energy recovery techniques. For an evaluation of the efficiency of such techniques, a life-cycle assessment is the most efficient tool according to [52]. With a life-cycle assessment it is possible to determine environmental burdens with the waste management process by the identification of used energy, materials and the emissions occurring during the treatment [53]. Landfilling without additional treatment cannot be categorized into energy recovery processes. Recycling residues can be treated in Combined Heat and Power (CHP) power plants, which makes energy recovery from landfilling processes possible [54]. Incineration reduces the waste that is not recyclable and that would otherwise be deposited completely in landfills [45]. Residues for the incineration process are ashes, which must be deposed in landfills, and residues that can be further treated in CHP plants for additional energy recovery [54]. Waste incineration has a negative impact on the environment due to the CO_2 emissions, whereby the municipal waste incineration has a higher impact than industrial waste incineration. Thereby the incineration of plastic produces the highest amount of emissions [47]. Regarding global warming potential, waste incineration has a lower impact than landfilling, as the methane emissions are comparably low [54]. Another option for energy recovery is the treatment of biodegradable waste for generating natural gas with anaerobic digestion [45]. The fact that only biodegradable waste can be used highlights the importance of high SSL levels. Compost is gained as a residual product from anaerobic digestion which can be used for agricultural and horticultural purposes. Ranked on the overall impact on the environment, anaerobic digestion is the most efficient solution [54]. As not all waste is biodegradable, other solutions must still be considered as well. Table 1 summarizes the three considered energy recovery processes.

Emerging and extension of other service sectors like hydrogen and the need for alternative mobility concepts lead to additional energy recovery potential for waste treatment. For extraction of the maximum amount of energy from waste treatment, networks for multiple sectors must be implemented [46]. The energy (and materials) generated from waste recovery can be further utilized by these sectors and the maximum potential of waste energy recovery can then be fully exploited.

3.2. Sewage Water to Energy

Production of fresh water with drinking quality can be executed by the treatment of sewage. Rather than only treating sewage for water recovery and in order to lower the negative environmental impacts, the treatment processes should additionally be laid out for the recovery of energy [55]. Sewage treatment always results into sludge production, regardless of the process. Sewage sludge can be a fundamental raw material for new energy generation technologies in a

Table 1: Comparison of Waste Energy Recovery Processes

Landfilling	**Incineration**	**Anaerobic Digestion**
Large land provision necessary	Immediate waste removal	Generation of natural gas
Long degradation times	Energy recovery	Compost as residual product
High Methane Emissions	High CO_2 emissions	Only for biodegradable waste
Without extension no energy recovered	Highest emissions for plastic	High SSL as not all waste is biodegradable
Residue treatment in CHP plants	Low methane emissions	Lowest impact on environment

sustainable society [56]. The treatment process and energy recovery processes can be implemented separately or in a combined system. A study from [57] found that the combined treatment with pipeline transport of the sludge is the most economical solution. Due to the high moisture content of sludge, drying processes in form of hydrothermal carbonization are necessary before utilizing the sludge for energy generation [58] in order to increase the overall procedure efficiency. Anaerobic digestion and combustion in CHP plants are the major energy recovery possibilities of sewage sludge. Methane production from sludge and grid injection into the gas grid is a potential economically feasible option as well, but the negative effects on the environment are high compared to the previously introduced options [59].

Anaerobic digestion reduces the load on the environment by sludge due to the volume reduction [60]. The use in anaerobic digestion can replace biodegradable waste as a source, which results into a reduction of methane production in the process that would occur at higher levels for biowaste anaerobic digestion [56]. Tarpani and Azapagic [61] found that sewage sludge anaerobic digestion plants can operate at profit, and so they are an economical solution for energy recovery. In CHP plants, sludge can be used as a substitution for coal, which makes it the most sustainable treatment option regarding fuel usage according to [59]. For combustion of sludge, the previously mentioned pre-drying process is an essential factor for sufficient efficiency [56]. Like for coal and waste combustion, the environmental impact of sludge incineration is high compared to anaerobic digestion [60]. Table 2 summarises the major aspects of anaerobic digestion and incineration of sewage sludge.

Both processes are rather new approaches for energy recovery, and so a further development in combination with a life-cycle assessment and investigations of the impact on human health are required [56]. The recovery rates and rev-

Table 2: Comparison of Sewage Sludge Energy Recovery Processes

Anaerobic Digestion	**Incineration**
Reduction of environmental load	Substitution of coal
Waste replaced as source	Most sustainable option regarding fuel use
Reduction of methane production	Pre-drying process for efficient combustion
Can operate at profit	High CO_2 emissions

enues that can be generated from recovered resources have a high impact on the feasibility of sludge treatment processes [61]. Advanced technologies for sewage treatment and further energy recovery can double the costs compared to conventional treatment according to [61], which makes process cost reductions in the future mandatory. All of the mentioned aspects lead to the conclusion that energy recovery is work in progress. As this approach has a lot of potential, it must be considered in future investigations regarding energy recovery in a sustainable society.

4. Implementation of Waste and Water into Energy Communities

In the next step, the demand services waste and water are investigated regarding possible introduction into an EC. Covering the demand of different services by linking the material- and energy flows of such services together is referred to as SC. An efficient SC approach in combination with ECs can be an implementation framework to reach a sustainable use of all energy and material services.

4.1. Sector Coupling

The general ideas and goals for SC were redefined by the European Union (EU) in [1]. For the achievement of climate neutrality by 2050 it is necessary to reduce the GHG emissions in energy service sectors that are more difficult to decarbonize. Therefore it is mandatory to plan the energy system across multiple sectors as a whole. To decrease the total energy consumption it is necessary to promote the most efficient conversion technologies. Another mentioned aspect in [1] is the active consumer participation, which can be executed in form of ECs. However, for the implementation of a circular energy system where many energy services interact with each other, the use of local energy sources, and the consideration of waste, sewage and residues for bioenergy production are needed. As the electricity sector is a sector with a high renewable energy generation potential, an electrification in other energy sectors, for example the utilization of heat pumps in the heat sector, can help to decarbonize the whole energy system. In order to reach that, it is required to protect the grid in form of new flexible energy provision units like storages or the Vehicle to Grid (V2G) concept. The energy markets must be made fit to promote the implementation of SC. In that connection the energy trading system that exists for electricity must be extended to new energy sectors. To achieve an utilization of SC in the energy system in the long term, the implementation process must be started with the infrastructure planning, as new infrastructure should promote the integration of different energy carriers. Possible grid extensions must be planned early enough to prevent an overload and operation problems. Another major aspect is the digitalization of the energy system, making it possible to determine the energy flows in the system in real time with smart meters [1].

SC has been examined in different research projects. Heat pumps have been confirmed as efficient additional flexibility options by [62]. Bashir et al. [63] see Power to Heat (P2H) as solution for the reduction of the emissions in the heat sector, as the excess electricity of renewable energy plants can be stored in heat storages and used to cover the heat demand. Power to Gas (P2G) technologies can provide an additional flexibility, as mentioned by [64]. According to [65], an efficient implementation of a SC concept depends on the characteristics of the supplied energy and the energy demand. Another mentioned aspect by [65] is that with SC it is possible to continuously substitute fossil energy sources, and also integrate renewable energy supply into other energy sectors than electricity, which was also brought up by [1]. Wietschel et al. [66] mentioned that SC must be implemented on the sectoral level, combining different households with industries, commercial buildings, transport and other services, as well as on the technological level, which is the energy conversion between different energy sectors with the corresponding infrastructure. Regarding the emission reduction, [67] found that energy generation and consumption scenarios where SC is applied led to the highest emission reduction. The value increase of renewable energy technologies due to SC was brought up by [68] as an additional advantage. Basically, all the considered papers agree on the fact that SC makes the cost-effective decarbonization of the energy system possible.

4.2. Energy Community Concepts

Above the concept of ECs is the goal of increasing the share of renewable energies in generation. ECs are considered as a conception that helps to promote the decentral generation of renewable energy and use the generated energy more efficient. The idea behind ECs is, that multiple entities use generated energy together to increase the self-consumption of renewable energies in order to relief the distribution grid. Participants of ECs thus share energy with each other, whereby not all participants must be in possession of a generation plant [2], [3]. On the regulatory level, ECs are defined in the EU guideline 2019/944 [3]. National laws are derived from this guideline, but are constructed on the national level, which leads to different implementation of ECs in the countries. On the European legal level it is distinguished between Citizen Energy Community (CEC) and Renewable Energy Community (REC). A CEC is a legal entity that consists of natural or legal persons that provide electricity to the community participants, whereas the participation in these communities must be free and open to everyone. RECs have the same framework as CECs with the difference that the generated energy in the community must be obtained from renewable generation plants and that other energy sources than electric energy can be shared within the community. Furthermore, the participation is geographically limited, as a major goal of RECs is to trade renewable energy locally to relief the higher grid levels of the distribution grid. The aim is to offer financial benefits in form of reduced grid fees for community trading to participants [2], [3]. The most frequently mentioned energy sources shared in ECs are electricity and heat, while the consideration of gas, cooling, mobility or hydrogen is also an option. In order to reach the maximum possible renewable energy introduction, a holistic view on the concept of ECs is necessary, where the implementation of waste and water are considered as well [69].

4.3. Implementing Waste and Water Usage into Energy Communities

As this approach is rather new, the implementation has not been examined in detail in existing papers. Therefore, possible studies that offer suitable approaches to this topic are considered.

Weight-based pricing of waste

Waste being charged independently of the accruing amount gives away a lot of potential. Weight-based charges have been investigated in different papers so far. With these charges, the polluter-pays principle, for which higher amount of disposed waste leads to higher costs for the perpetrator, is applied. Such charges can give incentives to reduce waste. Early studies regarding this topic in [70] found that a weight-based price should be preferred to a volume based price. In the investigations of [71], weight-based prices had a strong impact on the amount of emerging waste. Specifically, the total waste collection decreased by 42 % in the course of this study. For non-recyclable waste, the reduction was even higher with 56 %. Similar studies in Sweden by [72] found that 20 % less household waste was collected. In these studies, the problem of illegal dumping was mentioned, which could increase with the introduction of weight-based prices. An important implementation aspect of weight-based prices was brought up by [73], as costs reduction should be possible for people who are willingly to spend time and effort rather than money for waste reduction options. A major problem for the implementation of weight-based prices according to [74] is the lack of information given to people regarding their accruing waste and possible reduction. Dunne et al. [75] carried out a study on such pricing concepts in Ireland, where they found that people support weight-based pricing, as long as the price level does not increase to an unacceptably high level. In their paper, the problem of necessary investment for determination of the accruing waste for each household by the disposal companies was brought up, which might not be economically feasible without financial support instruments. An idea of [76] introduced volume based charges in form of disposal bags that are pre-paid and whose costs rise with corresponding size. However, in developed countries, such a concept should only be a temporary solution, as not the whole potential of weight-based prices can be exploited with this approach. Thøgersen [77] found that monetary aspects have less impact on the waste reduction than personal and social attitudes. Thus it is possible to implement weight-based prices into ECs, where the participants aspire to reduce waste together. A possibility in that context would be the collection of the community waste as a whole and charging of the shares to the participants depending on the volume of waste arising from their consumption. Weight-based waste disposal prices can hence be a possible tool for promoting waste reduction within an EC.

Water Consumption in Communities

This topic has barely been investigated yet. The existing studies mainly address consumption behaviour of different households. Seyranian et al. [78] investigated the impact of four different water consumption strategies, including the comparison to other households in the neighbourhood, reduction of water consumption within a group, personal identification in form of self-actualization and by giving water saving tips to consumers. Social aspects turned out to be the most efficient strategy for the reduction of the water consumption. In [79], the impact of feedback regarding water consumption on the residential level is examined. Thereby, the feedback included the actual and mean consumption of water, the ranking out of 100 within a community and a feedback in form of emoticons. As kind of gamification, the consumption of the households was compared to the mean water consumption, which could help to give incentives for water reduction. Consumers with a high water consumption decreased their consumption when they got negative feedback in form of emoticons, while low water consumers reacted more strongly to the ranking feedback. According to [79] a further improvement of the feedback mechanism could be made by the comparison of current water consumption and past water consumption within a household. In [78] it is also mentioned that social aspects must be considered for the achievement of water consumption reduction. The comparison and feedback approach could be implemented into energy communities. A ranking might also be possible, in which the best users pay less for water in the community. Like for waste, this could be implemented by a common community price, where the share of charges is weighted on the water consumption.

Further Implementation Ideas

Additionally to the ideas in the previous section, possible implementation ideas regarding waste disposal and water consumption in communities that were brought up during a brainstorming process and that have not been further investigated yet are mentioned in this section. Similar to charges for a higher amount of waste, charges could be set for insufficient waste separation. Potential penalties for the whole community would then be charged according to the SSL of the single community participants. Thereby the problem is that the SSL is hard to determine, which could prevent such concepts from being implemented. The sharing of devices within a community, for example lawn mowers, washing machines or cars, could reduce the emerging waste in the community. For communities with industrial participants, it could be possible to give certain devices a second life in private usage. The quality of gadgets might not be high enough anymore to fulfil the purposes of the industry, while it might still be high enough for private use. Existing know-how regarding reparation in a community can lead to not always having to dispose of broken equipment immediately, thus avoiding waste. All these aspects do not have a direct connection with energy, but such community operations can still be considered as sustainable. Moreover financial savings could be generated by the community members as reparation costs and costs for new devices can be saved.

Water usage in communities can primary be expanded by the set up of a community ground water well or other technologies to gain water for community purposes, which are mainly processes not requiring drinking water quality, as for the higher quality, additional treatment plants would be necessary. The gained water can thereby not be transported via the public pipelines, and so a second parallel pipeline system for the community would then be required. An utilization of community ground water wells might then be limited to simple purposes like irrigation. A future concept for water usage in periods with increasing water scarcity might be the implementation of water consumption rights (similar to CO_2 consumption rights). Depending on how such concepts are implemented, trading and sharing of water consumption rights within the community could be possible. Participants that save water can thereby have the option to sell water consumption rights to other community members and gain financial benefits from their reduced water consumption. However, since these are only possible future scenarios, they will not be discussed further in this paper.

For both, waste and water, energy recovery technology can be provided by industrial partners in communities. For this reason, these technologies are also considered in the SC model in the following section

5. Sector Coupling Model

5.1. Goals and Functionalities of the Model

SC models describe the interaction between different energy sectors, whereas in the majority of these models, energy flows between different nodes are being evaluated based on certain criteria. Such models can be found in [80], [81], [82], [83] or [84]. They all have in common that waste and water are not further considered sectors in their model. Therefore, an own model is developed, including both sectors, which is presented in figure 4. Additionally, the conversion technologies for waste and water are summarized in table 3.

In this model, the energy sectors are presented in square blocks. Additionally to the traditionally considered sectors electricity, heat and gas, waste and water as energy sources are considered as well. For a holistic approach, the inclusion of cooling, hydrogen and mobility must be considered as well. These energy service blocks are starting and ending points for energy flows. For a mathematical definition of the energy blocks, the law of conservation of energy can be applied, where it is determined that the incoming energy flows that increase the amount

Table 3: Overview Waste and Water Energy Recovery Technologies

Technology	**Input**	**Output**	**Description**
Waste Combustion	Waste	Electricity, Heat	Using waste instead of coal for incineration
Waste to Biogas	Waste	Gas	Anaerobic Digestion of Biowaste
Waste to Biofuel	Waste	Car Fuel	Biofuel out of waste for car powering
Fermentation	Waste	Hydrogen	Biological treatment of waste for hydrogen production
Sewage Treatment Plant	Sewage	Clean Water, Sludge, Heat	Recovery of water with additional exhaust heat and by-products
Sewage Combustion	Sludge	Electricity, Heat	Using sludge instead of coal for incineration
Anaerobic Digestion	Sludge	Gas	Sludge as source for anaerobic digestion
Microbial Fuel Cell	Sludge	Electricity	Innovative Technology for electricity generation from sewage sludge
Sewage Water to Hydrogen	Sewage	Hydrogen	Hydrogen recovery of sewage by fermentation

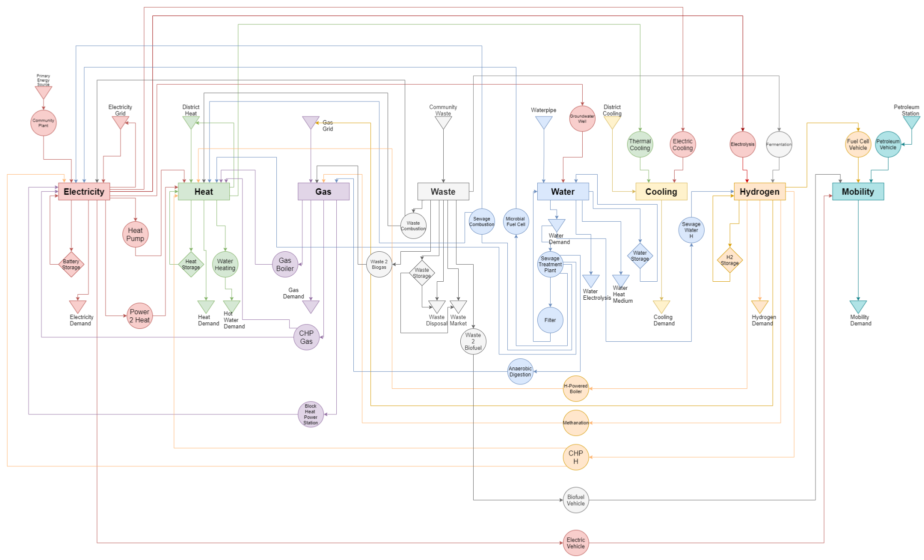

Figure 4: Sector Coupling Model

of energy in the block are considered positive and the outgoing energy flows that decrease the energy in the block are considered negative. This law can be applied to each energy block and is a fundamental mathematical condition for the whole model. The transition between different energy services is presented in form of flow arrows, whereby the colour of the arrow is set based on the source of the energy transition to be able to determine the source quicker when applying the law of conservation of energy for each block. Thus the arrows represent the outgoing and incoming energy flows in the blocks. For a transition between different energy services, conversion technologies are required, which are represented in form of circles and are coloured based on the input energy in figure 4. In the mathematic model, the conversion technologies are described by the input energy, the output energy, conversion factors respectively conversion efficiencies and by operating costs of the technology. Such conversion technologies are major components of a SC models, as they allow the interaction between different sectors. Storage systems are introduced as technologies allowing energy flows within the same sector, which are represented as a rhombus in figure 4. The use of storages makes it possible to store a surplus of energy within a sector at a certain time and to release it at other times when the energy is needed. Like the conversion technologies, storage technologies are described by input and output energy, as well as storage efficiency, respectively losses of the energy while being stored. For a holistic view on SC, such technologies cannot be neglected. A certain amount of energy for the different sectors must come from external sources, represented as triangulars. Single sources are dependent on generation profiles, like the generated electricity from decentral power plants or the accruing waste, while other sources are implemented to fulfil the law of conservation of energy for each energy sector. Such sources are generally external, so the energy obtained from them causes energy costs. It is up to the model to determine which quantity of purchased energy makes financial sense in the process. The main motivation of energy services is the coverage of an energy demand for external purposes. In the SC model, the energy demand is represented as triangle as well, whereas the major difference to energy source triangles is, that the energy flows come from the services and do not end in them. As mathematical input parameter for the model, the energy demand is given in form of load profiles, which are considered as output parameters in the law of conservation of energy.

5.2. Considered Conversion Technologies

After the description of the model in general, the considered conversion technologies are described more in detail. Electricity can be gained externally by purchase from the electricity grid or by generation with self-owned power plants. The electricity sector has a special role, as the electrification of other sectors is seen as solution to decarbonize other energy sectors by [1]. Conversion to the heat sector is achieved by heat pumps, which is an option to cover the heat demand. Additionally P2H technology can be used to store electricity by conversion into heat. Electricity is also a fundamental source for the use in electric cooling processes, hydrogen production with electrolysis and as fuel for electric vehicles. Regarding the water sector, the electric energy is used to power a groundwater well. Electricity conversion processes are therefore very versatile. Compared to that, heat is mainly used for the coverage of heat demand, hot water demand, and occasionally for thermal cooling technologies. Heat occurs in many processes as unwelcome by-product, as it is associated with losses. Thus a lot of conversion processes result into heat as output energy. Gas is generally considered as not sustainable, with the exception of green gas. It is mainly used in gas boilers, block heat stations or CHP plants for coverage of electricity and heat demand, as well as for other external processes that are gas-powered. Due to the increasing outdoor temperatures, the cooling sector is gaining importance. As there are no mentionable conversion technologies for this sector, it is only considered for the coverage of a specific cooling demand in the model. Hydrogen on the other hand can be used for many different conversion processes like boilers or CHP plants for covering the electricity and heat demand, as well as for methanation to produce green gas. Fuel cell vehicles, powered by hydrogen, are also seen as fundamental for the decarbonization of the mobility sector, so hydrogen has a lot of potential in SC concepts. Regarding mobility, each person has a specific mobility demand that must be covered by different types of cars. The major technologies thereby are electric vehicles, fuel cell vehicles, biofuel vehicles and traditional petroleum vehicles, whereas the latter should be replaced in the future for a decarbonization of this sector. For waste and water the considered conversion technologies are based on the energy recovery processes mentioned in section 3. Additionally to waste combustion, the generation of hydrogen via fermentation and the generation of biofuel for vehicle propulsion are represented in the model. As not all of the accruing waste can be disposed immediately, waste storages respectively waste collection bins must be implemented in the model, which store the waste until specific disposal times. Further investigations regarding waste could include an emerging waste market, in which revenues are generated by selling certain shares of the waste for reuse purposes. As the model represents SC in a sustainable society, such innovative concepts are implemented for the processing of future research questions. Water energy conversion technologies are represented by sewage water treatment processes for energy recovery. In addition to the already mentioned sludge incineration and anaerobic digestion, microbial fuel cells for electricity generation and the gain of hydrogen from sewage are considered in the model. A certain share of the exhaust heat from sewage water treatment can be used for heating. Water serves as a medium for electrolysis and as a heat medium, which must be considered as additional water demand.

5.3. Summary of the Model Approaches

In summary, the model contains conditions in form of the law of conservation of energy for each sector, where the main goal is to cover the external energy demand by energy transitions between different sectors and purchases from external sources, The energy transitions are described with conversion efficiencies. For each energy conversion, storage and purchase, costs emerge. The goal of the model is to determine the energy flows between the different energy sectors by an optimization in form of minimizing the total costs of the whole SC processes. It shows that waste and water can be implemented in such SC concepts, as they can interact with other energy sectors via energy recovery processes. Due to the large amount of energy conversion processes considered in the model, it is necessary to keep the conversion equations and the mathematical descriptions of the external sources, the demand and the costs as simple as possible to avoid long computing times for the optimization. An extension of the model for ECs can be done by aggregating the total energy demand of the community and by considering only the available conversion technologies that are existing in the community. With such a model, it is possible to analyse and address future questions on the topic of SC in energy communities, taking into account the waste and water sector.

5.4. Model Implementation Barriers and Challenges

For the fully developed model with all functionalities, barriers and challenges for the implementation in reality must be overcome. Therefore, potential execution issues of the model are analyzed in this section. For the implementation of the model in real use cases, a huge amount of consumer and process related data as model input parameters are required. This data must be collected or measured, processed and updated for all prosumers and consumers under consideration in order to always take into account current data. The vast amount of data as model input parameters can lead to long computation times, which limits the possibility of mathematical description of the technology equations. Additionally, not all investigated conversion technologies are fully developed yet, which can hinder their implementation on the large-scale. This results in a loss of the ability to accurately represent reality through the technology equations. Conversion technologies must be provided by certain prosumers and consumers that are considered in the model. These technologies are mostly capital-intensive, which means that in reality it will not always be achievable to provide all possible conversion technologies. The model does not provide investment decisions, which means that the presence of each conversion technology is determined via the input data, not in the optimization. This could result to minor energy flows for certain technologies, that might not be high enough to be able to economically justify the investment in the technology. The feasibility of an investment is thus determined in a further analysis rather than directly in the model.

Social and regulatory aspects can also hinder a successful model execution in reality, as the consideration of many different energy sectors leads to a high level of complexity. Generally, waste and water are yet to be considered in the same context as energy sectors like electricity and heat, so the raise of awareness in society about the potential of the inclusion of these sectors in a holistic energy system is a major challenge. Consumers applying sector coupling concepts need a lot of self awareness about their energy consumption. In addition, personal interest on getting the most out of the different energy sectors is required by the consumers and thus the model is only applicable for a certain consumer group, in which the consumers are willingly to put effort into improvement of their energy consumption and usage, even if their cost savings do not reflect the amount of effort used, which might occur in certain cases. Here it is up to the legislator to promote the implementation of sector coupling concepts like the one presented in the model. However, in order to be able to apply the model successfully in reality, the model outputs must be further evaluated after the optimization process. It is thereby required to examine the determined energy, mass and volume flows and eventually remove certain unfeasible conversion technologies for further runs of the model with the same input data. After that, a more detailed analysis of the results can take place, which means that the model application in reality is a multi-stage process. In summary, the developed model is a tool for the processing of issues regarding waste and water implementation into SC concepts and ECs, but for the implementation in real use cases, it cannot be expected to answer all research questions within the first processing step without further analysis.

5.5. Application of the Model in Use Cases

In order to make the function of the model clearer, the application of the model in possible use cases is described. The demand of the different energy sectors must be covered by available conversion technologies, as well as by purchase from the public grid. With the application of the developed model, the best possible use of different available conversion technologies leading to the lowest costs is determined. It is thus realizeable to examine if the implementation of different conversion technologies is economically feasible. In most cases, the electricity demand is covered mainly by grid consumption and own generation with small decentralized power plants, while the gas demand is covered only by grid consumption. Heat generation technologies like gas boilers and heat pumps are already present in many households. By applying the model in different use cases, financial benefits for additional consideration of waste and water treatment can be evaluated. While waste combustion is implementable on the household level, large scale treatment plants for waste and water, like sewage water treatment plants or anaerobic digestion plants, must rather be provided by industrial companies than by households themselves. Therefore additional investigations can contain a community foundation of households with industrial partners, where the latter could provide more conversion technology options. With the model it is achievable to determine the optimum use of conversion technologies in different use cases, whereas the differences between no consideration of waste and water as energy sectors, the consideration of both, and the participation in energy communities with industrial partners can be examined. Figure 5 shows the workflow for the processing of such use cases.

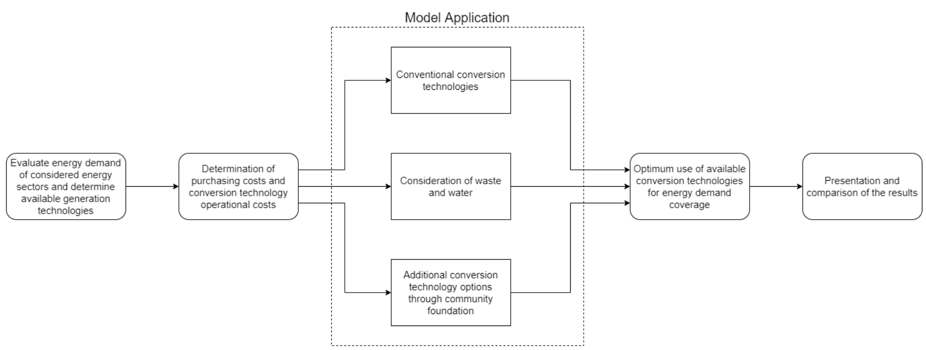

Figure 5: Workflow for Use Cases

In the first step, the energy demand for all considered energy sectors is evaluated and available energy generation plants and conversion technologies are determined. If waste is part of the examination, the accruing waste must be determined as well. In the next step, the costs for the operation of the conversion technologies as well as purchasing costs from external sources must be evaluated. The model is then applied to given use cases, considering different conversion technology options depending on their availability. Results and outputs of the model lead to the optimum use of the available conversion technologies, which can be presented and compared for a detailed result description.

5.6. Empirical model verification using a theoretical use case

In this theoretical use case, the application of the model on a theoretical use case is examined. The aim is to show in concrete terms how to proceed in the model. Therefore a single household with the energy sectors electricity, heat and gas is considered as a use case. The inclusion of waste and water energy recovery technologies is included in this use case as well. Storage technologies are neglected to keep the example simple. Figure 6 shows the configuration under consideration.

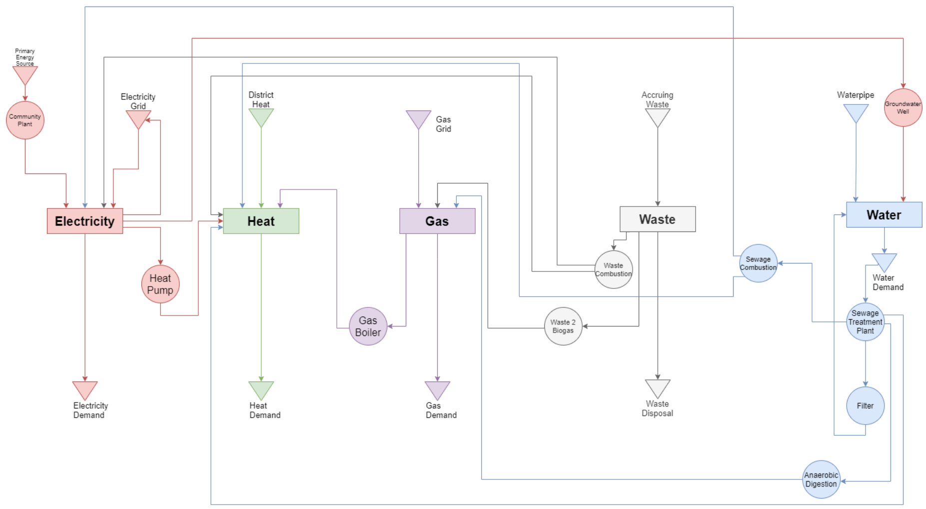

Figure 6: Theoretical Use Case

For the processing of the use case, the energy consumption profiles for electricity, heat and gas, respectively the energy demands must be given. Electrical energy generation from the household power plant is another predefined parameter in the model. The water demand and accruing waste also need to be known. However, in the processing of the use case, consumption and generation profiles are predefined and energy, mass and volume flows are evaluated in the optimization process. To determine the converted energies between different sectors, the needed technology equations must be specified with conversion factors if energy is generated from mass and volume flows or vice versa, respectively conversion efficiencies if input and output parameter have the same dimension. The following equation shows the relation between input and output variables. It must be considered that the input and output values are time dependent and are determined for each timestep in the model.

$$x_t^{j,k} = \eta^{conversion} \cdot x_t^{i,k} \tag{1}$$

Thereby, x is the input or output variable. This parameter can either be an energy (for electricity, heat and gas) with the unit kWh, a mass (for waste) with the unit kg or a volume (for water) with the unit m^3. The index i shows which energy sectors the input variable originates from, while the index j shows the same for the output variable. In this theoretical use case, the energy sectors can be electricity, heat, gas, waste or water. Further indicators of which conversion technology the parameters come from are the index k. The unit of the conversion factor can be determined with the following equation.

$$\left[\eta^{conversion}\right] = \frac{\left[x_t^{j,k}\right]}{\left[x_t^{i,k}\right]} \tag{2}$$

If more than one conversion process is required for the generation of a useful output parameter (like for sewage treatment), the conversion factors along the alteration chain must be multiplied together. In addition to the efficiencies, it is important to have knowledge about the process costs. Operating costs are incurred when carrying out a transformation process, and are usually dependent on the amount of input (energy, mass or volume) that is processed. For the considered use case it is necessary to specify the operation costs of the existing conversion units. These costs are further consulted in the cost minimization respectively the optimization. As not all transformation processes might be economically feasible and a certain amount of energy must be obtained from the public grid, additional energy purchase costs might emerge in the use case, which are dependent on the amount of purchased energy. The purchasing costs in addition with the conversion process costs result in the total costs of the use case. All these aspects lead to the following target function of the optimization problem.

$$\min C^{total} = \min(\sum_{processes} C^{process} + \sum_{EnergySectors} C^{purchase}) \tag{3}$$

The law of the conversion of energy must be applied to each energy sector. In the case of waste the law can be seen as mass balance and for water as volume balance. For the considered use case, the law is applied according to figure 6. To keep a better overview in the model, the predetermined parameters are indicated in capitals. Parameters that are determined in the optimization process are given in lowercase. This results into the following contraints of the optimization problem.

Electricity

$$\begin{split} Q_t^{el,PV} + q_t^{el,GridPurchase} + q_t^{el,sludgeCombustion} + q_t^{el,wasteComb} = \\ Q_t^{el,Demand} + q_t^{el,FeedIn} + q_t^{el,HP} + q_t^{el,groundwaterwell} \end{split} \tag{4}$$

Heat

$$\begin{split} q_t^{heat,GridPurchase} + q_t^{heat,HP} + q_t^{heat,sludgeCombustion} \\ + q_t^{heat,wasteComb} + q_t^{heat,GasBoil} + q_t^{heat,sewageTreatment} \\ = Q_t^{heat,Demand} \end{split} \tag{5}$$

Gas

$$\begin{aligned} q_t^{gas,GridPurchase} + q_t^{gas,Waste2Gas} + q_t^{gas,AD} \\ = Q_t^{gas,Demand} + q_t^{gas,GasBoil} \end{aligned} \tag{6}$$

Waste

$$\begin{aligned} M_t^{waste,Accruing} \\ = m_t^{waste,WasteDisposal} + m_t^{waste,WasteComb} + m_t^{waste,waste2Gas} \end{aligned} \tag{7}$$

Water

$$\begin{aligned} v_t^{water,Pipeline} + v_t^{water,groundwaterwell} + v_t^{water,waterRecovery} \\ = V_t^{water,Demand} \end{aligned} \tag{8}$$

The equations of the present conversion technologies in the use case are additional constraints in the model. With the given generation and consumption profiles of the theoretical example case, the optimisation problem can be solved and the energy flows that occur at minimum total costs can be determined.

As a theoretical use case without actual data is presented and the model concept is yet to be implemented in a computational model, expected results are presented. The energy flows determined in the optimization process are dependent on the given consumption and generation profiles. Especially the electric energy production with the household's power plant offers many possibilities, as the produced energy can be used for the coverage of the energy demand of more energy sectors than just the electricity sector. This results in additional flexibilities. The electricity grid can thereby be reliefed as not all of the excess energy is fed into the grid if other economic alternatives exist. An increase of the energy demand in one sector leads to additional energy flows in all sectors. Depending on the efficiencies and costs, an increase of properly disposed waste might result into a decrease of the gas purchased from the public grid. Further inclusion of waste and water as energy sectors may lead to additional cost savings if the energy recovery technologies are efficient enough. The theoretical case shows that a multitude of energy, mass and volume flows already occur in the interaction of a few conversion technologies and energy sectors. Despite the resulting increase in complexity, this can lead to more efficient operation of the entire energy system in the long term.

6. Conclusions

For sustainable waste treatment it is necessary to reduce the emerging waste. Therefore, waste management concepts must be implemented, in which the reduction, collection, transport, processing, as well as disposal and reuse of the accruing waste are set. The overall goal of waste management is to decrease the waste that is deposited in landfills, as this causes treat to the environment and covers a lot of area, that could be prevented by efficient management concepts. In addition to the waste reduction, it is required to improve waste separation, as a well functioning separation is required for efficient recycling processes and further treatment of waste. Waste reduction, separation and recycling are strongly dependent on social aspects. To improve the concepts, it is necessary to raise awareness on their importance and provide financial incentives to promote an efficient implementation. Similar to waste management concepts, water management considers the more efficient use of water and includes water reduction and the reuse of water, which can further reduce the required amount of water and improve the security of supply, as not the whole water demand must be covered by water with highest drinking quality. Like for waste, it is necessary to raise awareness regarding water consumption, as most consumers do not have enough knowledge on their water consumption.

Future developments allow a more sustainable waste treatment, for example the recovery for the production of heat and electricity. This has the advantage that waste is removed and used for energy generation at the same time. The two major processes considered in the literature are incineration and anaerobic digestion. To determine the overall impact of the processes, it is necessary to carry out a life-cycle assesment. Incineration leads to high CO_2 emissions, while the methane emissions are comparably low. Anaerobic digestion uses waste for biogas production and has a low impact on the environment compared to incineration. Sustainable use and recovery of water, also in higher temporal solution, can be achieved by further treatment of sewage. Similar to waste, the sewage sludge can be used for anaerobic digestion or incineration. It can be seen that energy recovery of waste and water has a lot of potential and that both should be considered as energy generation options in future energy systems.

SC help to decarbonize different sectors of the energy system and continuously substitute fossil energy sources. For an holistic view it is necessary to consider the interaction between the different sectors, as with this view it is possible to get the maximum out of each energy sector. Active consumer participation also plays an important role in SC, thus this approach can be extended in ECs. Further applications regarding ECs could promote waste reduction in form of weight-based disposal costs and water reduction through consumption comparison within a community. The common objective of reducing waste and water within a community can motivate the participants taking initiatives. This leads to the conclusion that reduction concepts should be implemented for whole communities rather than for single persons.

Traditional SC models can be extended by the recovery processes for waste and water. A lot of conversion processes emerge in a holistic view on the energy systems, and so it is required to develop a mathematical model to investigate issues regarding SC with consideration of more than just the traditionally examined sectors electricity, heat and gas. Such an approach is implemented in the model in figure 4. This model can be used for the examination of the optimum use of different conversion technologies that are covering the energy demand in different energy sectors by applying the workflow in figure 5. Further investigations could include investment decisions on the conversion technology which are presented in the figure. Another option could be the implementation of conversion processes more in detail or an extension of the model by additional conversion processes and emerging energy sectors. As the demand for alternative mobility concepts is increasing and vehicles tend to be used for other purposes than transport, like electric vehicles for grid stabilization, a more detailed modelling of the transport sector would be another extension option.

For future investigations, the sectors waste and water cannot be neglected while investigating energy system issues. Both sectors have a lot of potential for more efficient processes within the sectors, for interaction with other sectors in SC concepts and for an implementation into ECs. The joint use of conversion technologies in energy communities and the common endeavor to reduce water usage and waste can lead to a more sustainable society.

Acknowledgement

This work is done in the "Hybrid Local Sustainable Communities" project [85] and is supported with the funds from the Climate and Energy Fund and implemented in the framework of the RTI-initiative "Flagship region Energy" within Green Energy Lab

References

[1] European Commission, "Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions," 2020.

[2] European parliament and council of the European union, "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.

[3] European parliament and council of the European union, "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.

[4] M. M. Mekonnen and A. Y. Hoekstra, "Four billion people facing severe water scarcity," *Science Advances*, vol. 2, no. 2, 2016. [Online]. Available: https://advances.sciencemag.org/content/2/2/e1500323

[5] A. Kan, "General characteristics of waste management: A review," *Energy Educ Sci Technol Part A*, vol. 23, pp. 55–69, 2009.

[6] J. K. Seadon, "Sustainable waste management systems," *Journal of Cleaner Production*, vol. 18, pp. 1639–1651, 2010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652610002672

[7] A. J. Morrissey and J. Browne, "Waste management models and their application to sustainable waste management," *Waste Management*, vol. 24, pp. 297–308, 2004, landfill Process Modelling. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0956053X03001818

[8] T. Russo, K. Alfredo, and J. Fisher, "Sustainable water management in urban, agricultural, and natural systems," *Water*, vol. 6, pp. 3934–3956, 2014. [Online]. Available: https://www.mdpi.com/2073-4441/6/12/3934

[9] A. Demirbas, "Waste management, waste resource facilities and waste conversion processes," *Energy Conversion and Management*, vol. 52, pp. 1280–1287, 2 2011.

[10] S. Altin, A. Altin, B. Elevli, and O. Cerit, "Determination of hospital waste composition and disposal methods: a case study," *Polish Journal of Environmental Studies*, vol. 3, pp. 251–255, 2003.

[11] S. A. Sarkodie and P. A. Owusu, "Impact of covid-19 pandemic on waste management," *Environment, development and sustainability*, pp. 1–10, 8 2020. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/32863738https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7447614/

[12] J. J. Klemeš, Y. V. Fan, R. R. Tan, and P. Jiang, "Minimising the present and future plastic waste, energy and environmental footprints related to covid-19," *Renewable and Sustainable Energy Reviews*, vol. 127, p. 109883, 7 2020.

[13] J. M. Ekmann, J. C. Winslow, S. M. Smouse, and M. Ramezan, "International survey of cofiring coal with biomass and other wastes," *Fuel Processing Technology*, vol. 54, pp. 171–188, 3 1998.

[14] L. Giusti, "A review of waste management practices and their impact on human health," *Waste Management*, vol. 29, pp. 2227–2239, 8 2009.

[15] P. Vasanthi, S. Kaliappan, and R. Srinivasaraghavan, "Impact of poor solid waste management on ground water," *Environmental Monitoring and Assessment*, vol. 143, pp. 227–238, 2008. [Online]. Available: https://doi.org/10.1007/s10661-007-9971-0

[16] A. N. Kumar and I. F. Russel, "Introduction," *International Journal of Pattern Recognition and Artificial Intelligence*, vol. 14, pp. 1–2, 2000. [Online]. Available: https://doi.org/10.1142/S0218001400000027

[17] A. Uygur and F. Kargi, "Biological nutrient removal from pre-treated landfill leachate in a sequencing batch reactor," *Journal of Environmental Management*, vol. 71, pp. 9–14, 2004.

[18] W. Yang, H. sik Nam, and S. Choi, "Improvement of operating conditions in waste incinerators using engineering tools," *Waste Management*, vol. 27, pp. 604–613, 1 2007.

[19] M. Balat, "Progress in biogas production processes," *Energy Educ Sci Technol*, vol. 22, pp. 15–36, 2008, cited By 48.

[20] S. Bandyopadhyay, "Source composite curve for waste reduction," *Chemical Engineering Journal*, vol. 125, pp. 99–110, 12 2006.

[21] V. W. Y. Tam and C. M. Tam, "Waste reduction through incentives: a case study," *Building Research & Information*, vol. 36, pp. 37–43, 2008. [Online]. Available: https://doi.org/10.1080/09613210701417003

[22] D. Simpson, "Institutional pressure and waste reduction: The role of investments in waste reduction resources," *International Journal of Production Economics*, vol. 139, pp. 330–339, 9 2012.

[23] D. Knickmeyer, "Social factors influencing household waste separation: A literature review on good practices to improve the recycling performance of urban areas," *Journal of Cleaner Production*, vol. 245, p. 118605, 2 2020.

[24] Y. Ma, H. Wang, and R. Kong, "The effect of policy instruments on rural households' solid waste separation behavior and the mediation of perceived value using sem," *Environmental Science and Pollution Research*, vol. 27, pp. 19 398–19 409, 2020. [Online]. Available: https://doi.org/10.1007/s11356-020-08410-2

[25] D. Y. Xu, Z. Y. Lin, M. P. Gordon, N. K. Robinson, and M. K. Harder, "Perceived key elements of a successful residential food waste sorting program in urban apartments: stakeholder views," *Journal of Cleaner Production*, vol. 134, pp. 362–370, 10 2016.

[26] K. Stoeva and S. Alriksson, "Influence of recycling programmes on waste separation behaviour," *Waste Management*, vol. 68, pp. 732–741, 10 2017.

[27] I. Ajzen, "The theory of planned behaviour: reactions and reflections," *Psychol. Health*, vol. 26(9), pp. 1113–1127, 2011.

[28] N. Leeabai, S. Suzuki, Q. Jiang, D. Dilixiati, and F. Takahashi, "The effects of setting conditions of trash bins on waste collection performance and waste separation behaviors; distance from walking path, separated setting, and arrangements," *Waste Management*, vol. 94, pp. 58–67, 7 2019.

[29] M. Struk, "Distance and incentives matter: The separation of recyclable municipal waste," *Resources, Conservation and Recycling*, vol. 122, pp. 155–162, 7 2017.

[30] L. Xu, M. Ling, and Y. Wu, "Economic incentive and social influence to overcome household waste separation dilemma: A field intervention study," *Waste Management*, vol. 77, pp. 522–531, 7 2018.

[31] R. van der Brugge, J. Rotmans, and D. Loorbach, "The transition in dutch water management," *Regional Environmental Change*, vol. 5, pp. 164–176, 2005. [Online]. Available: https://doi.org/10.1007/s10113-004-0086-7

[32] J. Rotmans, M. V. Asselt, K. Molendijk, R. Kemp, F. Geels, and G. Verbong, "Transitions and transition management the case of an emission-low energy supply," 2000. [Online]. Available: http://inis.iaea.org/search/search.aspx?orig_q=RN:32010301

[33] R. J. Cureau and E. Ghisi, "Reduction of potable water consumption and sewage generation on a city scale: A case study in brazil," *Water*, vol. 11, 2019. [Online]. Available: https://www.mdpi.com/2073-4441/11/11/2351

[34] M. Vallès-Casas, H. March, and D. Saurí, "Examining the reduction in potable water consumption by households in catalonia (spain): Structural and contingent factors," *Applied Geography*, vol. 87, pp. 234–244, 10 2017.

[35] H. Abu-Bakar, L. Williams, and S. H. Hallett, "Quantifying the impact of the covid-19 lockdown on household water consumption patterns in england," *npj Clean Water*, vol. 4, p. 13, 2021. [Online]. Available: https://doi.org/10.1038/s41545-021-00103-8

[36] B. Randolph and P. Troy, "Attitudes to conservation and water consumption," *Environmental Science and Policy*, vol. 11, pp. 441–455, 8 2008.

[37] A. L. Soenderlund, J. R. Smith, C. Hutton, and Z. Kapelan, "Using smart meters for household water consumption feedback: Knowns and unknowns," *Procedia Engineering*, vol. 89, pp. 990–997, 1 2014.

[38] Y. Strengers, "Negotiating everyday life: The role of energy and water consumption feedback," *Journal of Consumer Culture*, vol. 11, pp. 319–338, 2011. [Online]. Available: https://doi.org/10.1177/1469540511417994

[39] N. Nouri, F. Balali, A. Nasiri, H. Seifoddini, and W. Otieno, "Water withdrawal and consumption reduction for electrical energy generation systems," *Applied Energy*, vol. 248, pp. 196–206, 8 2019.

[40] Z. Khan, P. Linares, and J. García-González, "Integrating water and energy models for policy driven applications. a review of contemporary work and recommendations for future developments," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 1123–1138, 1 2017.

[41] Green Facts, "Facts on water resources: A summary of the united nations world water development report 2." 2009.

[42] E. Friedler, "Water reuse - an integral part of water resources management: Israel as a case study," *Water Policy*, vol. 3, pp. 29–39, 1 2001.

[43] A. N. Angelakis, T. Asano, A. Bahri, B. E. Jimenez, and G. Tchobanoglous, "Water reuse: From ancient to modern times and the future," *Frontiers in Environmental Science*, vol. 6, p. 26, 2018. [Online]. Available: https://www.frontiersin.org/article/10.3389/fenvs.2018.00026

[44] J. Dyson, "'one water': Concept for the future?" 8 2016.

[45] S. Dlamini, M. D. Simatele, and N. S. Kubanza, "Municipal solid waste management in south africa: from waste to energy recovery through waste-to-energy technologies in johannesburg," *Local Environment*, vol. 24, pp. 249–257, 2019. [Online]. Available: https://doi.org/10.1080/13549839.2018.1561656

[46] S. Ohnishi, M. Fujii, M. Ohata, I. Rokuta, and T. Fujita, "Efficient energy recovery through a combination of waste-to-energy systems for a low-carbon city," *Resources, Conservation and Recycling*, vol. 128, pp. 394–405, 1 2018.

[47] Y. C. Chen, "Evaluating greenhouse gas emissions and energy recovery from municipal and industrial solid waste using waste-to-energy technology," *Journal of Cleaner Production*, vol. 192, pp. 262–269, 8 2018.

[48] D. Moya, C. Aldás, G. López, and P. Kaparaju, "Municipal solid waste as

a valuable renewable energy resource: A worldwide opportunity of energy recovery by using waste-to-energy technologies," pp. 286–295, 10 2017.

[49] S. Yi, Y. C. Jang, and A. K. An, "Potential for energy recovery and greenhouse gas reduction through waste-to-energy technologies," *Journal of Cleaner Production*, vol. 176, pp. 503–511, 3 2018.

[50] M. Giugliano, S. Cernuschi, M. Grosso, and L. Rigamonti, "Material and energy recovery in integrated waste management systems. an evaluation based on life cycle assessment," *Waste Management*, vol. 31, pp. 2092–2101, 9 2011.

[51] S. Consonni and F. Viganò, "Material and energy recovery in integrated waste management systems: The potential for energy recovery," *Waste Management*, vol. 31, pp. 2074–2084, 9 2011.

[52] R. Clift and L. Wright, "Relationships between environmental impacts and added value along the supply chain," *Technological Forecasting and Social Change*, vol. 65, pp. 281–295, 11 2000.

[53] F. Consoli, "Guidelines for life-cycle assessment," *A Code of Practice*, 1993. [Online]. Available: http://ci.nii.ac.jp/naid/10003576024/en/

[54] B. Milutinović, G. Stefanović, P. S. Đekić, I. Mijailović, and M. Tomić, "Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multi-criteria analysis," *Energy*, vol. 137, pp. 917–926, 10 2017.

[55] W. Verstraete, P. V. de Caveye, and V. Diamantis, "Maximum use of resources present in domestic "used water"," *Bioresource Technology*, vol. 100, pp. 5537–5545, 12 2009.

[56] J. Peccia and P. Westerhoff, "We should expect more out of our sewage sludge," *Environmental Science & Technology*, vol. 49, pp. 8271–8276, 7 2015, doi: 10.1021/acs.est.5b01931. [Online]. Available: https://doi.org/10.1021/acs.est.5b01931

[57] T. Miyanoshita, N. Oda, N. Hayashi, M. Fujiwara, and H. Furumai, "Economic evaluation of combined treatment for sludge from drinking water and sewage treatment plants in japan," *Journal of Water Supply: Research and Technology-Aqua*, vol. 58, pp. 221–227, 5 2009. [Online]. Available: https://doi.org/10.2166/aqua.2009.043

[58] C. He, A. Giannis, and J. Y. Wang, "Conversion of sewage sludge to clean solid fuel using hydrothermal carbonization: Hydrochar fuel characteristics and combustion behavior," *Applied Energy*, vol. 111, pp. 257–266, 11 2013.

[59] N. Mills, P. Pearce, J. Farrow, R. B. Thorpe, and N. F. Kirkby, "Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies," *Waste Management*, vol. 34, pp. 185–195, 1 2014.

[60] J. Hong, J. Hong, M. Otaki, and O. Jolliet, "Environmental and economic life cycle assessment for sewage sludge treatment processes in japan," *Waste Management*, vol. 29, pp. 696–703, 2 2009.

[61] R. R. Z. Tarpani and A. Azapagic, "Life cycle costs of advanced treatment

techniques for wastewater reuse and resource recovery from sewage sludge," *Journal of Cleaner Production*, vol. 204, pp. 832–847, 12 2018.

[62] A. Rinaldi, M. C. Soini, K. Streicher, M. K. Patel, and D. Parra, "Decarbonising heat with optimal pv and storage investments: A detailed sector coupling modelling framework with flexible heat pump operation," *Applied Energy*, vol. 282, p. 116110, 1 2021.

[63] A. A. Bashir, A. Lund, M. Pourakbari-Kasmaei, and M. Lehtonen, "Optimizing power and heat sector coupling for the implementation of carbon-free communities," *Energies*, vol. 14, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/7/1911

[64] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable european energy system," *Energy*, vol. 160, pp. 720–739, 10 2018.

[65] P. Lichtenwoehrer, L. Abart-Heriszt, F. Kretschmer, F. Suppan, G. Stoeglehner, and G. Neugebauer, "Evaluating spatial interdependencies of sector coupling using spatiotemporal modelling," *Energies*, vol. 14, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/5/1256

[66] M. Wietschel, P. Plötz, B. Pfluger, M. Klobasa, A. Eß{}er, M. Haendel, J. Müller-Kirchenbauer, J. Kochems, L. Hermann, B. Grosse, L. Nacken, M. Küster, J. Pacem, D. Naumann, C. Kost, R. Kohrs, U. Fahl, S. Schäfer-Stradowsky, D. Timmermann, and D. Albert, "Sektorkopplung: Definition, chancen und herausforderungen," 2018, urn:nbn:de:0011-n-4845758. [Online]. Available: http://hdl.handle.net/10419/175374

[67] J. Gea-Bermúdez, I. G. Jensen, M. Münster, M. Koivisto, J. G. Kirkerud, Y. kuang Chen, and H. Ravn, "The role of sector coupling in the green transition: A least-cost energy system development in northern-central europe towards 2050," *Applied Energy*, vol. 289, p. 116685, 5 2021.

[68] C. Bernath, G. Deac, and F. Sensfuß, "Impact of sector coupling on the market value of renewable energies – a model-based scenario analysis," *Applied Energy*, vol. 281, p. 115985, 1 2021.

[69] G. Fridgen, R. Keller, M. F. Körner, and M. Schöpf, "A holistic view on sector coupling," *Energy Policy*, vol. 147, p. 111913, 12 2020.

[70] D. Fullerton and T. Kinnaman, "Household responses to pricing garbage by the bag," *American Economic Review*, vol. 86, pp. 971–984, 1996.

[71] V. Linderhof, P. Kooreman, M. Allers, and D. Wiersma, "Weight-based pricing in the collection of household waste: The oostzaan case," *Resource and Energy Economics*, vol. 23, pp. 359–371, 10 2001.

[72] L. Dahlén and A. Lagerkvist, "Pay as you throw. strengths and weaknesses of weight-based billing in household waste collection systems in sweden," *Waste Management*, vol. 30, pp. 23–31, 1 2010.

[73] S. Scott and D. Watson, "Introduction of weight-based charges for domestic solid waste disposal," 5 2006.

[74] A. Davies, F. Fahy, and D. Taylor, "Mind the gap! householder attitudes

and actions towards waste in ireland," *Irish Geography*, vol. 38, pp. 151–168, 2005.

[75] L. Dunne, F. J. Convery, and L. Gallagher, "An investigation into waste charges in ireland, with emphasis on public acceptability," *Waste Management*, vol. 28, pp. 2826–2834, 12 2008.

[76] I. Welivita, P. Wattage, and P. Gunawardena, "Review of household solid waste charges for developing countries - a focus on quantity-based charge methods," *Waste Management*, vol. 46, pp. 637–645, 12 2015.

[77] J. Thøgersen, "Monetary incentives and recycling: Behavioural and psychological reactions to a performance-dependent garbage fee," *Journal of Consumer Policy*, vol. 26, pp. 197–228, 2003.

[78] V. Seyranian, G. M. Sinatra, and M. S. Polikoff, "Comparing communication strategies for reducing residential water consumption," *Journal of Environmental Psychology*, vol. 41, pp. 81–90, 3 2015.

[79] Y. Otaki, K. Ueda, and O. Sakura, "Effects of feedback about community water consumption on residential water conservation," *Journal of Cleaner Production*, vol. 143, pp. 719–730, 2 2017.

[80] M. Pavičević, A. Mangipinto, W. Nijs, F. Lombardi, K. Kavvadias, J. P. J. Navarro, E. Colombo, and S. Quoilin, "The potential of sector coupling in future european energy systems: Soft linking between the dispa-set and jrc-eu-times models," *Applied Energy*, vol. 267, p. 115100, 6 2020.

[81] M. Robinius, A. Otto, P. Heuser, L. Welder, K. Syranidis, D. S. Ryberg, T. Grube, P. Markewitz, R. Peters, and D. Stolten, "Linking the power and transport sectors—part 1: The principle of sector coupling," *Energies*, vol. 10, 2017. [Online]. Available: https://www.mdpi.com/1996-1073/10/7/956

[82] K. Boblenz, V. Frank, and B. Meyer, "Energy system analysis for evaluation of sector coupling technologies," *Fuel*, vol. 254, p. 115658, 10 2019.

[83] K. Qu, T. Yu, L. Huang, B. Yang, and X. Zhang, "Decentralized optimal multi-energy flow of large-scale integrated energy systems in a carbon trading market," *Energy*, vol. 149, pp. 779–791, 4 2018.

[84] L. Kriechbaum, G. Scheiber, and T. Kienberger, "Grid-based multi-energy systems—modelling, assessment, open source modelling frameworks and challenges," *Energy, Sustainability and Society*, vol. 8, p. 35, 2018. [Online]. Available: https://doi.org/10.1186/s13705-018-0176-x

[85] Green Energy Lab, "Hybrid LSC," https://greenenergylab.at/projects/hybrid-lsc/, 2021, Online; accessed 02 July 2021.