sustainability

MDPI

Article

Energy and Business Synergy: Leveraging Biogenic Resources from Agriculture, Waste, and Wastewater in German Rural Areas

Moritz Pollack [1,*], Andrea Lück [2], Mario Wolf [2], Eckhard Kraft [2] and Conrad Völker [1]

[1] Department of Building Physics, Bauhaus-University Weimar, 99423 Weimar, Germany; conrad.voelker@uni-weimar.de

[2] Department of Biotechnology in Resource Management, Bauhaus-University Weimar, 99423 Weimar, Germany; andrea.lueck@uni-weimar.de (A.L.); ulrich.mario.wolf@uni-weimar.de (M.W.); eckhard.kraft@uni-weimar.de (E.K.)

* Correspondence: moritz.pollack@uni-weimar.de; Tel.: +49-3643-584847

Abstract: The imperative to transform current energy provisions is widely acknowledged. However, scant attention has hitherto been directed toward rural municipalities and their innate resources, notably biogenic resources. In this paper, a methodological framework is developed to interconnect resources from waste, wastewater, and agricultural domains for energy utilization. This entails cataloging existing resources, delineating their potential via quantitative assessments utilizing diverse technologies, and encapsulating them in a conceptual model. The formulated models underwent iterative evaluation with engagement from diverse stakeholders. Consequently, 3 main concepts, complemented by 72 sub-concepts, were delineated, all fostering positive contributions to climate protection and providing heat supply in the rural study area. The outcomes' replicability is underscored by the study area's generic structure and the employed methodology. Through these inquiries, a framework for the requisite energy transition, with a pronounced emphasis on the coupling of waste, wastewater, and agriculture sectors in rural environments, is robustly analyzed.

Keywords: energy transition; energy concepts; energy systems; rural area; biogenic residues; biogenic waste materials; agriculture; waste management; wastewater management; regional development

check for updates

Citation: Pollack, M.; Lück, A.; Wolf, M.; Kraft, E.; Völker, C. Energy and Business Synergy: Leveraging Biogenic Resources from Agriculture, Waste, and Wastewater in German Rural Areas. *Sustainability* **2023**, *15*, 16573. https://doi.org/10.3390/su152416573

Academic Editors: Domenico Licursi and Juan Hernández Adrover

Received: 10 November 2023
Revised: 2 December 2023
Accepted: 3 December 2023
Published: 5 December 2023

1. Introduction

To ensure the future livelihood of humankind, the international community adopted the 2030 Agenda in 2015. Consisting of 17 Global Sustainable Development Goals (SDGs) for socially, economically, and ecologically sustainable development, this agenda is a roadmap for the future that will enable people around the world to live in dignity while preserving the natural foundations of life in the long term. As part of the transition toward a more sustainable future for humankind, goal 7 seeks to strive away from the use of fossil fuels, such as natural gas, coal, and oil, by increasing the share of renewable energy in the global energy mix to significantly enhance energy efficiency [1]. Researchers have intensified their work to deliver solutions to meet the defined goals of the 2030 Agenda in terms of heat and electricity supply. New technologies are being developed, such as hydrogen-based combined heat and power units (CHP) [2], and the efficiency of existing technologies, such as solar panels, windmills, and gas turbines, has been continuously increased [3–7]. However, achieving the goals set forth by the 2030 Agenda appears to be challenging. In the past few decades, the world has experienced a rapid increase in primary energy consumption; from 1950 until the year 2023, it had more than doubled [8]. For the future, studies (e.g., [8]) have predicted an increase of 28% in global primary energy consumption from 13.8 billion tons of oil equivalent (bn toe) in 2016 to 17.6 bn toe in 2040. Of that predicted total increase, 40% will be covered by renewable energies. Therefore, the share of primary energy consumption accounted for by conventional energies will only decrease by 6% from 86% in 2016 to 80% in 2040. While the increase in the electricity sector in recent years is notable, the heating sector lacks an accelerating momentum [9].

The necessary shift toward renewable energies and higher energy efficiency does not only pose a technological challenge. It also requires a complex process of altering our current energy consumption and production methods at national, continental, and global scales [10]. The process of planning and implementing this transition is confronted by a range of challenges, including conflicting objectives and values, and it requires a navigation of the complexities and uncertainties associated with political and administrative considerations. Additionally, it involves the coordination of multiple stakeholders throughout the transition process [11].

Municipalities and local authorities play a pivotal role in driving energy planning and energy transition efforts [12,13]. In the past, the primary focus was on larger municipalities that have well-equipped staff with the necessary capabilities [14]. Recently, a gradual shift toward rural areas was observed [15,16], leading to the current implementation of a national law requiring each municipality in Germany to design a Communal Energy Plan (CEP). In light of the pursuit for renewable energies and heat waste as sole sources of usage for heating purposes, the aim of a CEP is to determine a climate-friendly and progressive heat supply at the municipal level as a long-term prospect and to identify measures of its implementation. The transformation toward a more renewable energy system must be ecological, economical, and socially acceptable [17]. Thus, each CEP should incorporate the local conditions of its municipality, such as the technical infrastructure systems, environmental and economic aspects, as well as human resources [18]. This shift is not surprising, given that approximately 90% of the European Union's territory is rural or predominantly rural, and slightly over half of the European population resides in such areas [19]. Rural areas offer the essential resources and suitable locations for renewable energy production [20–22].

In rural areas, a significant accumulation of agricultural residues and animal manure is evident [23,24]. Moreover, organic and green waste is generated, with some of it either remaining uncollected or being transported over substantial distances for treatment. Furthermore, additional biogenic resources can be derived from the wastewater sector, which frequently lacks modern technical infrastructure in Germany's rural regions [25,26]. Despite the inherent benefits, these three sources of biogenic resources are seldom integrated into a cohesive management system. Their utilization and coordinated management face a multitude of non-technical challenges, encompassing social, economic, and legislative dimensions [27,28]. These challenges include resource competition, conflicts over land use, environmental considerations, regulatory and policy obstacles, community acceptance, economic viability, and issues related to skills and training.

Managing entities like municipalities and municipal utilities is confronted with constrained resources in the forms of limited time, personnel, and expertise to proactively steer the development and execution of renewable energy concepts. This dilemma emerges from the juxtaposition of external challenges and the internal need for competence, all within the constraints of finite resources [29]. Consequently, there is a pressing need for guidance to assist local stakeholders in structuring the implementation of rural energy concepts that harmonize the wastewater, waste, and agricultural sectors, while being tailored to their unique circumstances.

In this context, the aim of this article is to demonstrate a systematic stakeholder-oriented approach to define viable energy concepts based on the integrated management of wastewater, biogenic waste, and agricultural residues. Based on a rural area in Germany, the suggested approach consists of several steps, including an in-depth analysis of the given situation in the case study area as well as an assessment of the economic and ecological consequences of executing these diverse concepts, considering the distinct material flows within the study area. Thus, the motivation of this study lies in offering rural stakeholders a guideline for investigating the individual local energetic potentials of utilizing residues from wastewater, waste, and agricultural sectors. In this way, this study adds a conceptual energy component that should be considered in the design process of CEPs for rural areas.

This article is structured into five sections. Following the introduction, a description of the study area, the methodological steps, and the analytical framework is provided in Section 2. In Section 3, details of how the methodological approach is applied and the identified energy concepts are presented. A discussion of the results is presented in Section 4. Finally, the findings are summarized in Section 5.

2. Materials and Methods

2.1. Study Area Description

The case study area (Figure 1) is the administrative union Am Ettersberg, consisting of 19 villages and three smaller towns in Germany. Additionally, three neighboring villages are part of the study area, as they are also members of the local wastewater association responsible for the administrative union Am Ettersberg. Located within a typical rural area in Thuringia, the study area holds approximately 9000 inhabitants and spans an area of nearly 100 km^2. Since 1990, the demographic change led to a significant decrease in population, whereas for the state of Thuringia, a loss of 8.7% has been predicted for the period from 2021 to 2042; this trend can be also observed in the study area [30].

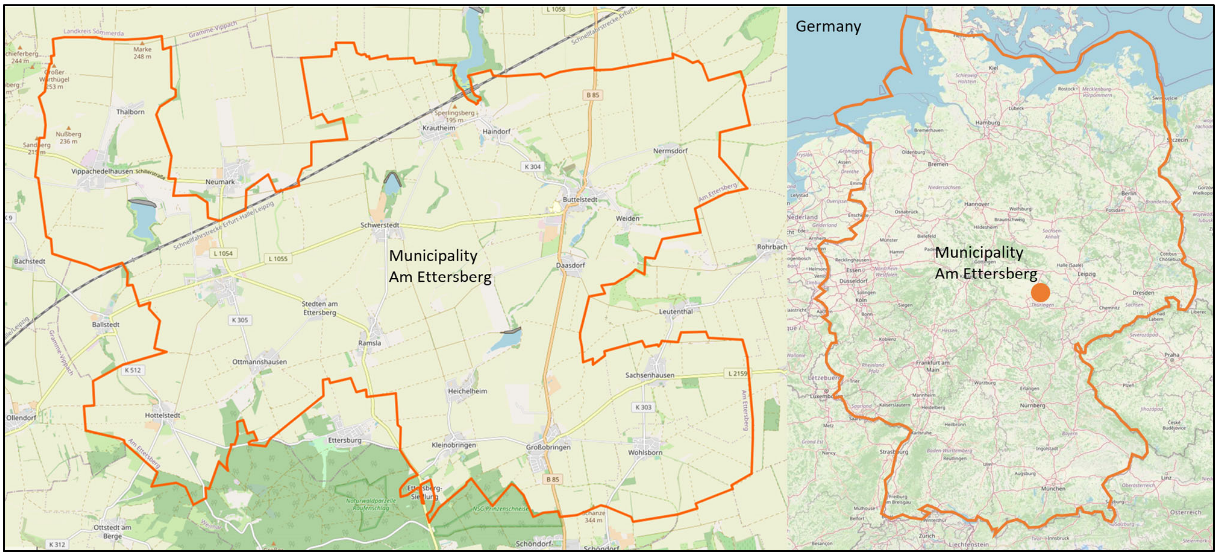

Figure 1. Map of the study area, the municipality Am Ettersberg, and its location in Germany [31].

With the purpose of providing reliable tasks in the public sector despite the demographic challenges, the administrative union Am Ettersberg was established in the year 2019 [32]. Prior to its establishment, an administrative union consisting of a smaller number of villages governed the area. From a communal perspective, today's administrative union is responsible for the energy transition and design of a CEP.

Aiming to overcome the dependence on fossil fuels, local authorities must define the future energy solutions for all areas under their jurisdiction (e.g., decentralized or grid-bound). This includes options for how renewable energies and industrial heat can be used in generating and distributing energy locally [33]. Another public task lies in the management of biogenic waste. This includes public loads, such as green cuttings, and waste in public areas, e.g., parks and roadsides. However, this public green waste is not collected properly and is disposed of in a non-compliant way to current state of the art. The same applies to private green biowaste.

Wastewater management in the municipality Am Ettersberg is widely decentralized, which is typical for the rural areas of Thuringia [34]. A wastewater association is responsible for providing adequate wastewater treatment in the study area. However, due to limited financial resources, the required infrastructure projects are considered long-term endeavors [35]. Currently, only a minority of residents within the operational zone have access to biological wastewater treatment. Fecal sludge disposal is costly, though it could potentially be harnessed for on-site energy generation. The remaining inhabitants lack access to state-of-the-art wastewater treatment, necessitating urgent action. Simultaneously, there exists an opportunity to implement more resource-efficient systems that facilitate synergy across various sectors.

Economically, agriculture is a driving force for the development of livable rural areas in Thuringia [36]. In addition to basic food production, the range of services includes the development of alternative sources of income. Specifically, the need for an increasing link with the energy industry is given. In 2016, Thuringian farmers operated 260 biogas plants, collectively supplying electricity to nearly 340,000 households [37]. As of 2023, the number of biogas plants has barely changed [38]. These dynamics are similarly observed in the farms situated within Am Ettersberg. Given the absence of other major corporations in the region, farms serve as the primary employers. The economic emphasis among them varies; some exclusively prioritize arable land products, while others engage in intensive livestock farming, frequently complemented by the operation of biogas plants.

2.2. Methodology

To identify suitable energy concepts for the study area, a systematic methodological approach was applied by the researchers (adopted from [39,40]). This approach is primarily based on the recommended steps for municipal energy planning [41,42], which involves conducting a thorough inventory analysis, assessing potential, and identifying actionable options. While previous models and methodologies for renewable energy supply in urban areas and communities have considered different kinds of biomass (e.g., [43–45]), there has been a notable absence of a combined examination of material flows despite its significant potential, particularly in rural areas [25].

Therefore, this study integrates the conventional approach of life cycle assessments (Goal and Scope–Life Cycle Inventory (Cradle to Grave)–Impact Assessment–Interpretation), which is commonly utilized for evaluating waste disposal pathways (see [46,47]) and resource planning [48]. The intention is to bridge the gap by applying this established methodology to the assessment of biomass in the context of renewable energy supply for municipalities. This novel approach not only extends the existing framework but also addresses a crucial aspect of rural energy planning by considering material flows and their potential impact on sustainable energy solutions.

This approach consists of the four following steps, which will be depicted in more detail below (Figure 2):

- Inventory analysis to assess the current technical infrastructures and biogenic material flows in the analyzed sectors in the study area;
- Potential analysis to identify suitable technology options to transfer biogenic residues into energetic potential;
- Conceptualization to define the energy concepts and their sub-concepts;
- Concept evaluation to identify the (dis)advantages of each sub-concept in reference to the current system.

Inventory analysis: The inventory analysis involves a comprehensive assessment of infrastructures and material flows within the waste management, wastewater management, and agricultural sectors, as well as the energy demand in the study area.

In the waste management sector, particular focus is placed on biowaste and private or municipal green waste, along with the respective collection systems and disposal routes, including the distances travelled. Additionally, any existing treatment facilities, especially those with energy output, such as biogas plants, are taken into account.

Within the wastewater management sector, the quantities and compositions of sewage sludge are of primary importance. This includes a consideration of pre-treatments and disposal routes, along with corresponding distances. Furthermore, sewage sludge treatment plants (including dewatering, drying, and digestion) within the area under consideration are documented. Future developments like the construction of municipal sewage treatment plants or the decommissioning of small-scale sewage treatment plants and related changes in sewage sludge generation are also considered.

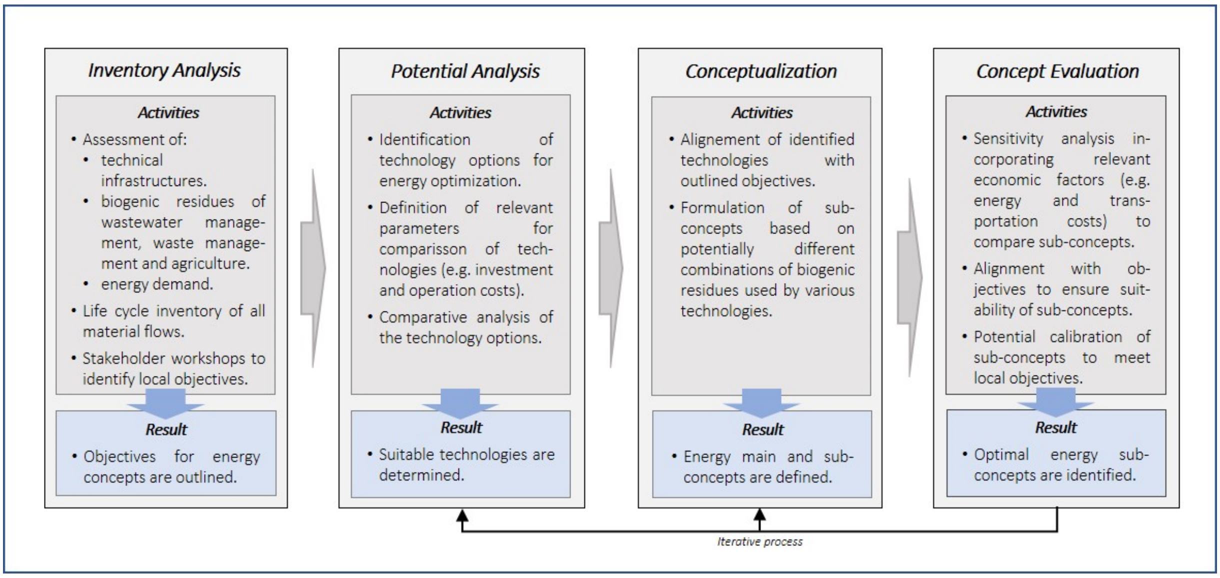

Figure 2. Conceptual framework of the methodology used.

In agriculture, the focus lies on previously unutilized material flows. This encompasses manure and compost, as well as residual straw. Additionally, existing agricultural biogas plants and their respective input materials are recorded. The energy demand within the area of interest plays a crucial role in determining the utilization of energies generated through new energy concepts. Local consumable energies such as heat and fuel are particularly relevant. The determination of heat demand should be spatially resolved and can be simplified through the use of statistical indicators (e.g., [49]) or can be derived from existing municipal heat planning. If there are no aggregated data available for calculating the heat demand of private households in rural municipalities due to a decentralized supply structure, it can be derived at the building level using the online tool TRAIL (see [44]). TRAIL provides the heat demand of private households in kWh/(m^2 of living space per year) in a 100 × 100 m grid for all Thuringian municipalities based on publicly accessible data (statistical data on building age [50] and typical heat demand by building age and type [50], with 3D buildings on the level of detail 2 (LoD2 city model) [51]). From the LoD2 city model, the living area for each residential building was determined following the TRAIL calculation algorithm [49]. Then, the heat demand per building was calculated as follows:

$$\mathrm{Q_{building}} = \mathrm{A} \cdot 0.8 \cdot \mathrm{n} \cdot \mathrm{C_{heat}} \tag{1}$$

where $\mathrm{Q_{building}}$ is the annual heat demand of a specific building, A is the building floor area, n is the number of floors, and $\mathrm{C_{heat}}$ is the specific heat demand in kWh/(m^2·a) of the corresponding tile in the 100 × 100 m grid [49]. The heat demand of non-residential buildings, for which no consumption data are available, as well as commercially used buildings, can be estimated based on the gross floor area of these buildings and their characteristic values depending on the type of use [52].

In addition to capturing the infrastructure, material flows, and energy demands of public entities and private households, these aspects should also be taken into account for relevant commercial and industrial enterprises. An overview of the captured data for the inventory analysis is given in Table 1.

Table 1. Captured data for inventory analysis.

	Energy Sector	Wastewater Sector	Waste Sector	Agriculture Sector
Material flows	Energy demand in households (heat, fuel)	Sewage sludge	Biowaste from households	Manure
			Private green waste	Compost
	Energy demand in industry (heat, fuel)		Municipal green waste	Residual Straw
			Landscaping materials	Further input material
Infrastructure		Pre-treatments	Collection system(s)	
		Disposal routes	Disposal routes	
		Treatment facilities	Treatment facilities	Biogas plant(s)

In the next step, a life cycle inventory of the current utilization pathways for all considered material flows in terms of costs, revenues, greenhouse gas emissions, carbon credits, and energy consumption are compiled using the available literature or operating data. Then, the abovementioned parameters are summed up across the pathways to determine the costs, revenues, emissions, credits, and cumulative energy expenditures for the existing system. The balance framework of the life cycle inventory is schematically shown in Figure 3.

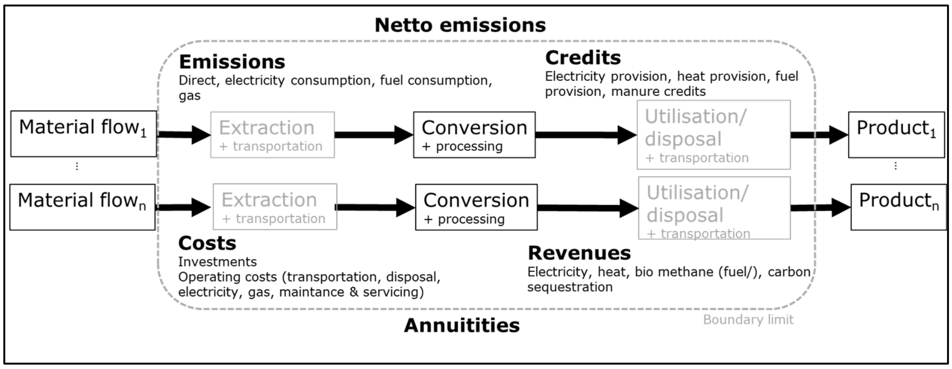

Figure 3. Balance framework of the life cycle inventory.

The energy content of the material flows should be determined to identify effective utilization routes at a later stage.

Utilizing this flow balance enables the identification of weaknesses in the current system, pinpointing areas such as outdated treatment technologies or unutilized material flows. Simultaneously, it is crucial to assess the objectives of local stakeholders in the study area concerning resource utilization, heat planning, and future developments, particularly in the context of energy resources.

Potential analysis: Potential analysis aims to identify various technology options (conversion technologies) for energy-optimized treatment and the effective utilization of material flows (adopted from [53]). This includes a special focus on technologies that allow for the combined treatment of multiple material flows from different sectors. Additionally, it involves identifying any potentially necessary technologies for the pre-treatment (provision technologies) of material flows. Furthermore, the analysis seeks to identify potential utilization technologies to harness the products generated through the application of conversion technologies.

In this context, relevant parameters for all identified technology options (provision, conversion, and utilization) should be determined. These parameters include investment costs, operating costs, revenues, lifespan, greenhouse gas emissions, carbon credits, and energy consumption. These factors are evaluated in relation to local specifics, such as the quantities of material flows to be treated and transportation distances.

Conceptualization: During this phase, the main concepts are formulated by aligning the identified technology options with the objectives set by regional stakeholders. Any material flows not addressed in the central conversion technology will have their existing utilization pathways incorporated into the main concepts to ensure that a complete life cycle inventory is prepared for each concept.

Additionally, sub-concepts are developed through the exploration of different combinations of treated material flows using the conversion technologies and potential utilization technologies to obtain the resulting products.

Concept evaluation: It is important to select a time frame (TF) for assessing energy concepts. This period is typically determined by the longest lifespan among all considered technology options. However, deviations may occur in cases of different planning scenarios at the local or higher levels.

Next, greenhouse gas emissions, carbon credits, and cumulative energy expenditures are calculated on an annual basis for each utilization pathway. The calculation of necessary investment costs, discounted expenses, and revenues are aggregated to a present value (PV) and then converted into equivalent annual cost (EAC) according to current guidelines for dynamic cost comparisons for water management facilities [54] using the Formulas (2) and (3):

$$\mathrm{PV} = \frac{\mathrm{I_0}}{(1+\mathrm{p})^{\mathrm{i}}} + \Sigma \frac{\text{operating costs}_{\mathrm{i}} * (1+\mathrm{g})^{\mathrm{i}} - \text{revenues}_{\mathrm{i}}}{(1+\mathrm{p})^{\mathrm{i}}} \tag{2}$$

where $\mathrm{I_0}$ is the investment cost, p is the interest rate, g is the annual price increase rate, and i is the year.

$$\mathrm{EAC} = \frac{\mathrm{PV}}{\mathrm{TF}} \tag{3}$$

Following this, the parameters mentioned above are aggregated across all material flows to determine the net emissions, EAC, and cumulative energy expenditures for each sub-concept. In the subsequent step, the greenhouse gas abatement potential (AP) and the greenhouse gas abatement costs (ACs) for all sub-concepts are computed as indicators for their climate change mitigation effects as well as economical performances. This is carried out by comparing the results of the calculations and energy savings obtained in the previous step with the results for the existing system using Formula (4):

$$\mathrm{AC} = \frac{\Delta\ \mathrm{EAC}}{\Delta\ \text{emissions}} = \frac{\mathrm{EAC_j} - \mathrm{EAC_0}}{\text{emissions}_{\mathrm{j}} - \text{emissions}_0} \tag{4}$$

where j indicates the values for the corresponding sub-concept, and 0 indicates the values for the existing system.

Finally, a sensitivity analysis is carried out, considering economically relevant parameters such as energy costs, transportation costs, price increases, interest rates, and the chosen time frame. This analysis helps identify the optimal concepts based on criteria like maximum greenhouse gas reduction potential, lowest greenhouse gas reduction costs, the best ratio of greenhouse gas savings to investment costs, and the best ratio of greenhouse gas reduction costs to investment costs. These findings are then aligned with local objectives and goals to identify the optimal sub-concept.

3. Results

Applying the previously described methodology to the study area requires a structured process. Therefore, the results will be presented below according to each of the four analytical steps.

3.1. Results of Inventory Analysis

Waste disposal is managed at the district level. The municipal waste management company is the entity responsible for waste disposal. Due to the rural structure of the study area and the resulting lack of economic viability for the separate collection of organic waste, the municipal waste management company set the goal of widespread on-site composting. In the study area, biogenic household waste was not yet separately collected. Therefore, it was collected together with residual waste in a pick-up system and subsequently loaded onto trucks at the district's depot located at a distance of approximately 30 km. From there, it was thermally treated in an incineration plant located about 140 km away. Since precise data on waste quantities in the municipality are not recorded, they must be estimated based on the quantities and compositions of waste for the entire district provided by the district works, as well as population figures. Information regarding the compostable fractions of household waste is available from the household waste analysis for 2016/2017 [55]. Green waste was collected through three containers located in the municipality, using a drop-off system. These containers contained private and municipal green waste.

Focusing on wastewater management, approximately 54% of the population was connected to a central municipal sewage treatment plant, 39% had access to a mechanical small-scale sewage treatment plant, and 7% had access to a fully biological small-scale sewage treatment plant. Consequently, the collected sludge primarily consisted of sludge from small-scale sewage treatment plants with a very high water content. The data on sludge production and composition were provided by the wastewater disposal entity of the study area. The sludge in the study area was not collected or treated centrally but rather disposed of at a large sewage treatment plant located approximately 30 km away.

In the study area, there are two large agricultural enterprises. In addition to plant production, their activities include the breeding of sows and dairy farming, along with the operation of a power-driven biogas plant. The heat generated by this biogas plant is utilized for heating the stables and buildings, although a significant portion remains unused.

The heat supply in the study area is characterized by a decentralized structure due to its rural nature, and there is no centralized heating network. The majority of heat generation is fossil-based, with a significant portion coming from heating oil, as only a few villages are connected to the gas network. Since there are no aggregated data available for the heat demand of private households in the rural municipality due to this decentralized supply structure, these were derived at the building level from the online tool TRAIL (see Formula (1)).

The data on heat demands were then consolidated using a heat cadaster. This was gradually expanded to include non-residential buildings for which consumption data are available (buildings owned by the municipality and industrial buildings). In addition, other municipal buildings for which no consumption data are available, as well as commercially used buildings, were added by estimating the heat demand based on the gross floor area of these buildings and their characteristic values depending on the type of use.

The electricity demand for private households in the study area was adopted from TRAIL. This was based on statistical data on average electricity demand per person. The municipality provided the electricity demand for the community (street lighting, sewage treatment plants, municipally owned buildings, etc.).

The energy demand for road transportation was extrapolated from the energy demand for Thuringia [56], using the population figures for the study area.

Based on the data collected as described above, a balance was created for the quantities and energy contents of material flows, as well as the costs, revenues, greenhouse gas emissions, carbon credits, and cumulative energy expenditures for the material flows generated in the study area, which include sludge, organic waste, green waste, cattle manure, swine manure, and residual straw. This is illustrated in Figure 4. The costs were discounted within a 30-year time frame using Formula (2) for comparison with the later energy concepts.

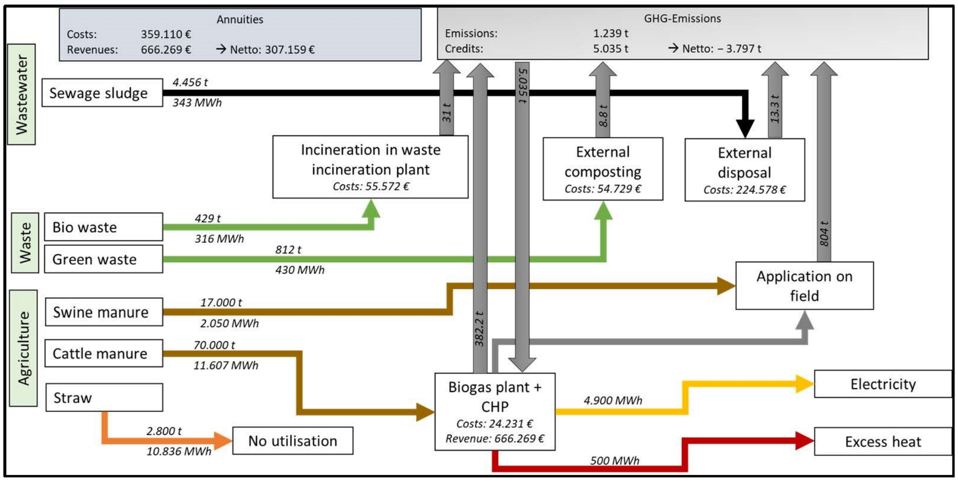

Figure 4. Schematic representation of the existing system and its life cycle inventory.

Notable negative points in the balance include particularly high emissions from the direct application of swine manure, elevated costs due to the external disposal of untreated sludge, the suboptimal disposal of high-calorific organic waste and green waste, and the underutilization of excess heat from the biogas plant.

In several workshops and discussions with stakeholders from the wastewater management sector (Managing Director of the wastewater disposal entity), waste management sector (Member of the Environmental Committee of the district), and agriculture sector (Managing Director/Department Head of the agricultural enterprises), as well as members of the municipal administration (Mayor, Energy Manager of the municipality, and Head of the Building Department), the objectives of each sector were discussed. The objectives were outlined as follows:

- Wastewater management: the aim is to reduce the high costs of external sludge disposal by implementing in-house treatment solutions.
- Waste management: this sector is open to cross-sector collaboration and partnerships.
- Agriculture: This sector's focus is on the continued operation of the existing biogas plant that is economically viable beyond the expiration of the state Renewable Energy Law (Erneuerbare-Energien-Gesetz (EEG)) subsidies. Also, this sector aims to explore opportunities for utilizing swine manure, especially for meeting their own energy needs.
- Municipality: the aim is to ensure a sustainable heat supply within the municipal area, with a preference for leveraging regional resources.

3.2. Results of Potential Analysis

To investigate how to transform the biogenic resources into energy, different technologies were catalogued, and their impacts were quantified. Based on a literature review (see [57–59]), biogas plants with power generation in combined heat and power units (CHP), fermentation with the upgrading to biomethane, combustion, gasification, hydrothermal carbonization (HTC), and pyrolysis were identified as suitable conversion technologies for the partial joint treatment of the relevant material flows in the study area. Their specific characteristics were documented in technology profiles.

In some cases, (pre-) processing steps are required for certain material flows. Likewise, only some of the technologies are suitable for certain material flows. Different products can be provided using the various conversion technologies identified from the literature review. These findings are summarized in the table below (Table 2).

Table 2. Investigated technology options, with (pre-) processing steps and outputs.

	Biogas Plant and CHP	**Biomethane Plant**	**Combustion**	**Gasification**	**Hydrothermal Carbonization**	**Pyrolysis**
Input						
Organic Waste	Shredding, separation of impurities	Shredding, separation of impurities	No	Drying	Yes	Drying
Green Waste	Shredding, separation of impurities	Shredding, separation of impurities	Drying	Drying	Yes	Drying
Sewage sludge	Yes	Yes	Drying	Drying	Yes	Drying
Cattle manure	Yes	Yes	No	No	Yes	No
Swine manure	Yes	Yes	No	No	Yes	No
Straw	Shredding	Shredding	Yes	Yes	Yes	Yes
Output						
Heat	Yes	No	Yes	Yes	No	No
Electricity	Yes	No	No	Yes	No	No
Fuel	No	Yes	No	No	Yes	Yes
Fertilizer/soil conditioner	Yes	Yes	No	No	Yes	Yes

To effectively harness the respective material flows and the resultant products, a range of extraction and utilization technologies is imperative. Regarding extraction technologies, consideration encompasses a separate collection of biowaste and straw extraction. As for utilization technologies, integration involves a heating network, mobile heat storage, a biomethane filling station, and biomethane injection into the gas grid.

3.3. Results of Conceptualization

Derived from the conversion technologies and aligned with the goals of local stakeholders, three primary concepts were discerned. By modifying the pertinent material flows and corresponding technology options for each concept, a total of 72 sub-concepts were delineated in accordance with the three main concepts.

3.3.1. Concept 1: Maximum Heat Provision

Based on the high heat demand identified in the inventory analysis and considering the structural suitability of a selected village in the study area, Concept 1 aims to provide the maximum amount of heat in the area through the establishment of a district heating network. Possible heat sources include the utilization of excess heat from the existing biogas plant, an expansion of this biogas plant for the utilization of treatment-requiring material flows, and the construction of a new heating plant. By varying the heating plant (combustion/gasification), the materials used (option 1: straw; option 2: green waste; option 3: straw + green waste), the configuration of the existing biogas plant (option 1: existing fermenter; option 2: new fermenter; option 3: without excess heat), and the biogas substrates used (option 1: cattle manure; option 2: cattle manure + sludge; option 3: cattle manure + organic waste; option 4: cattle manure + sludge + organic waste), a total of 48 sub-concepts were considered for Concept 1 (see Figure 5).

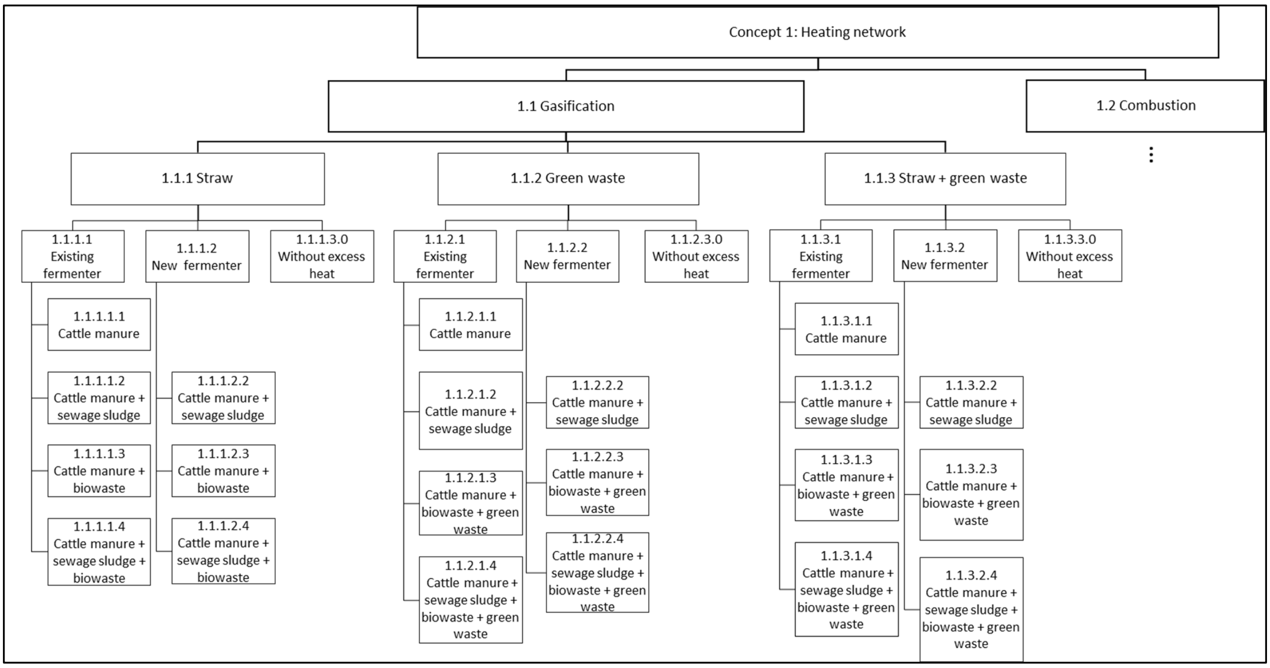

Figure 5. Schematic of sub-concepts for Concept 1.

3.3.2. Concept 2: Emission Minimization through Swine Manure Utilization

Due to the identified high greenhouse gas emissions from untreated swine manure in the study area, the digestion of this material presents significant potential for minimizing greenhouse gas emissions. Through the co-digestion of other treatment-requiring materials, synergistic effects can be harnessed, leading to significant cost savings and enhanced emission reductions. Moreover, this approach presents the prospect of producing climate-neutral energy products, including upgraded biogas, as well as electricity and heat. By varying the utilization technologies for biogas (option 1: CHP + mobile heat storage; option 2: upgrading to fuel; option 3: upgrading + injection into gas grid) and the biogas substrates used (option 1: swine manure; option 2: swine manure + sludge; option 3: swine manure + organic waste; option 4: swine manure + sludge + organic waste), 12 sub-concepts were identified for Concept 2 (see Figure 6).

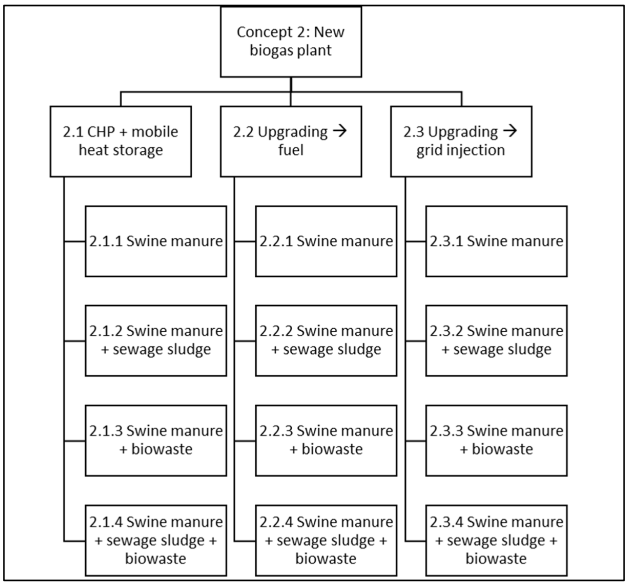

Figure 6. Schematic of sub-concepts for Concept 2.

3.3.3. Concept 3: Optimized Sludge Management

External sludge disposal constitutes a significant cost factor for the considered sectors. Achieving a more efficient local treatment of sludge is feasible by tapping into existing waste heat sources, such as the available biogas plant, or previously unexplored biomass potentials. Moreover, this approach opens up the possibility for producing high-quality biochar. Concept 3 introduces 12 sub-concepts by varying the sludge treatment technology (option 1: dewatering + drying; option 2: hydrothermal carbonization; option 3: pyrolysis), the heat provision (option 1: new biogas plant + CHP; option 2: existing biogas plant + CHP), the utilization of biochar from hydrothermal carbonization or pyrolysis (option 1: sludge disposal; option 2: soil conditioner; option 3: fuel), and the materials involved in hydrothermal carbonization (option 1: sludge; option 2: sludge + organic waste; option 3: sludge + organic waste + green waste) (see Figure 7).

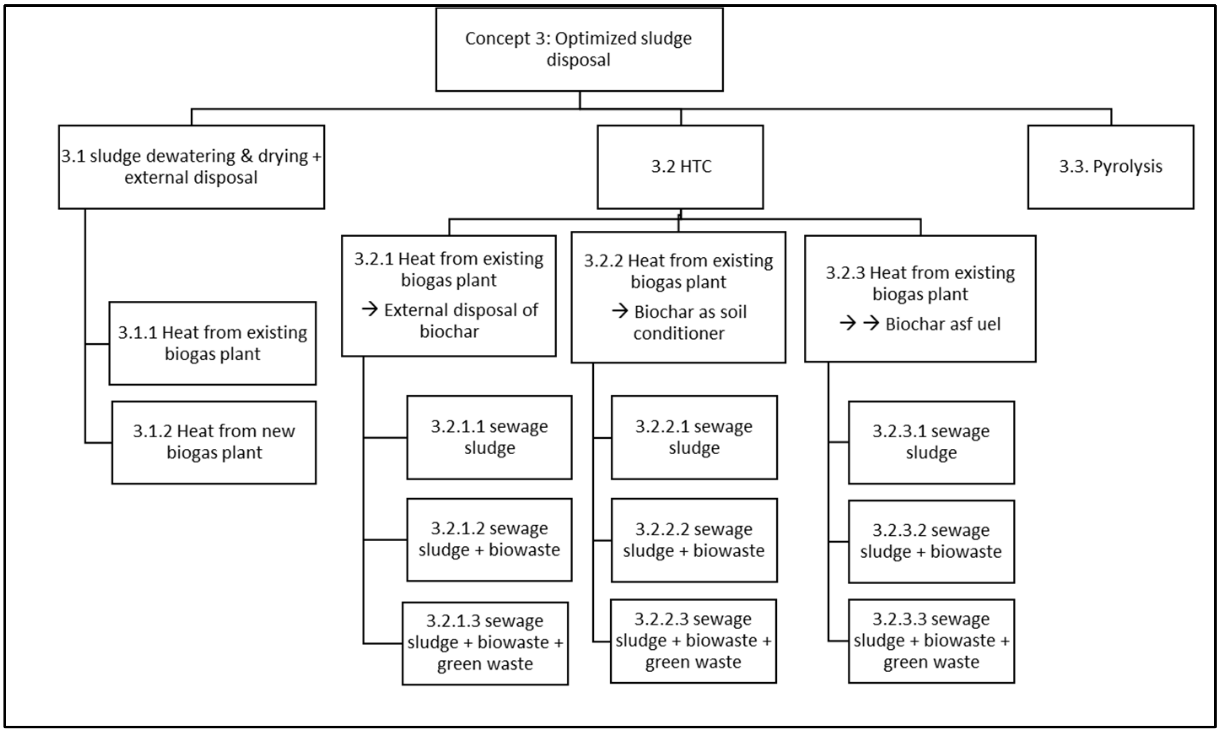

Figure 7. Schematic of sub-concepts for Concept 3.

3.4. Results of Concept Evaluation

Based on an Excel tool created for this case study, the necessary investment costs, discounted costs, and revenues for each utilization pathway, as well as greenhouse gas emissions and cumulative energy expenditures, were calculated on an annual basis for all the sub-concepts. These values were then summed for comparison within each main concept. By comparing them with the existing system, the required investment costs, greenhouse gas emission abatement potentials, greenhouse gas abatement costs, and energy savings were derived. The results are presented in a diagram (Figure 8). The diagram depicts the annual GHG abatement potential on the x-axis and the specific GHG abatement costs on the y-axis. The size of the circles corresponds to the investment costs required for the implementation of each sub-concept, and the color indicates their alignment with the main concepts. It is important to note that almost all the sub-concepts have negative GHG abatement costs, indicating that these sub-concepts are associated with financial savings or revenues.

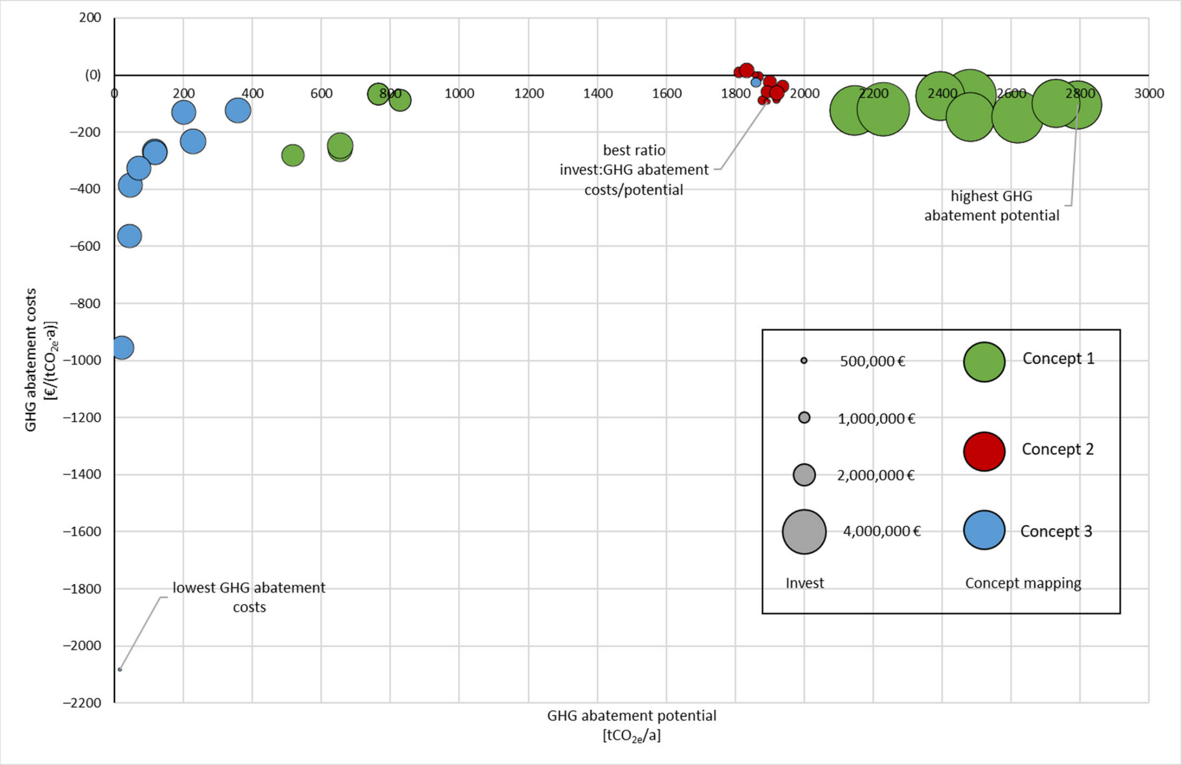

Figure 8. GHG abatement costs and potentials and investment costs of the evaluated concepts.

Depending on the prioritized objective, different concepts represent the optimum:

1. Establishing a district-heating network with the incineration of straw and green waste, along with the treatment of cattle manure, organic waste, and green waste, enables the highest greenhouse gas emission reductions. However, this option entails very high investments. As was the case before, sewage sludge would continue to be externally disposed without prior treatment, and swine manure would not be utilized in this sub-concept (see Figure 9).
2. The dewatering and drying of sewage sludge, using the excess heat from the existing biogas plant, offers the lowest GHG abatement costs, resulting in significant financial savings with manageable efforts. For this purpose, sewage sludge dewatering and drying facilities would be installed, which would receive the required heat from the existing biogas plant. Subsequently, the dried sewage sludge would continue to be disposed externally. The remaining material flows would be treated or disposed of in the same manner as in the existing system (see Figure 10).
3. The co-digestion of swine manure and sewage sludge presents the best ratio of investment costs to mitigation potential and mitigation costs. The generated biogas would be upgraded and subsequently distributed as fuel. The disposal routes for the remaining material flows remain the same in this sub-concept as in the existing system (see Figure 11).

A one-dimensional sensitivity analysis was conducted for the parameters including transportation costs, energy costs, interest rate, evaluation period, and price increase, as these parameters have a significant influence on the economic performance of the concepts aside from the investment costs. The remaining parameters that form the basis of the calculations were retained, since they are precisely known due to local conditions (e.g., distances and material flows) or can be considered secure based on thorough research (e.g., emissions), and no significant alterations are to be expected. The GHG abatement costs were used as the case study variable. In light of the significant uncertainties prevailing in recent years, particularly concerning costs, especially in the energy sector, the estimation of realistic parameter ranges proved to be a challenging task. Consequently, wide parameter ranges were chosen for the following parameters: interest rate, price increase, transportation costs, and energy costs. The volatile nature of these variables underscores the complexity of forecasting, making it difficult to establish well-founded parameter ranges.

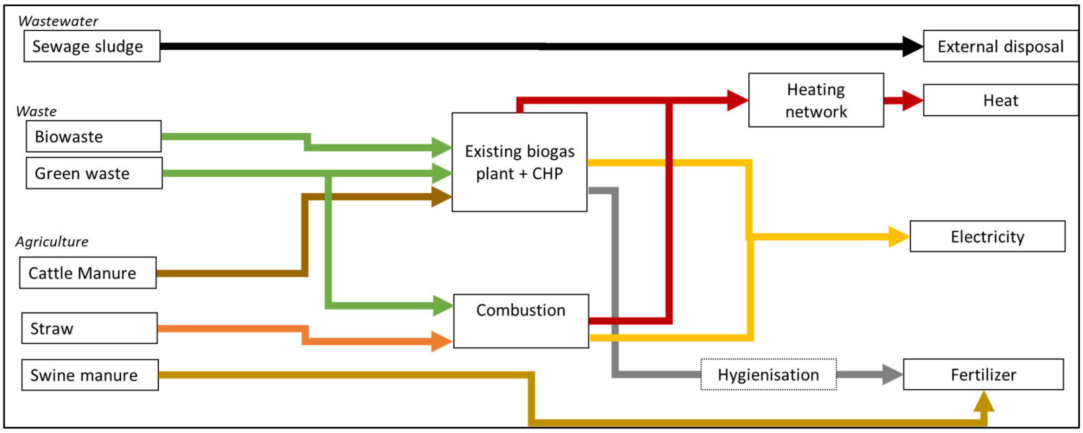

Figure 9. Schematic representation of the concept with the highest GHG reduction.

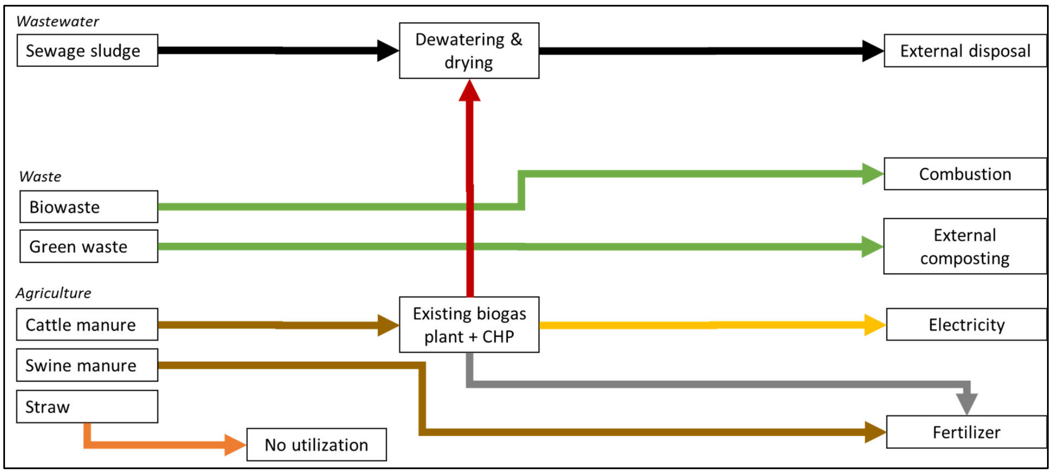

Figure 10. Schematic representation of the concept with the lowest GHG abatement costs.

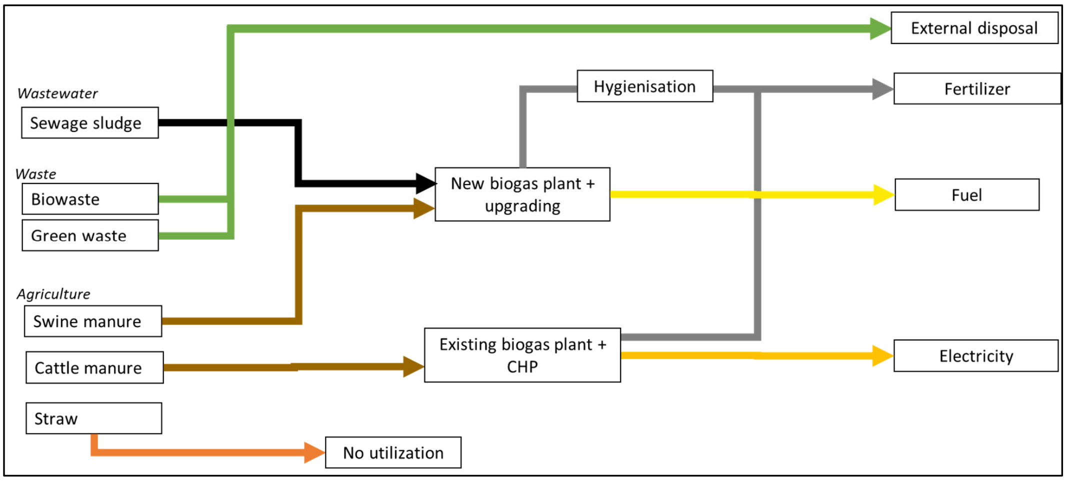

Figure 11. Schematic representation of the concept with the best ratio of investment costs to GHG abatement costs and potential.

The selection of the evaluation period typically aligns with the longest depreciation time of the system components under consideration. However, due to the extended operational lifetimes observed in certain technologies, such as heat networks, the evaluation period was expanded to up to 50 years. This expansion was motivated by the recognition that some technologies exhibit longer lifespans in practical applications than initially anticipated. Conversely, given the anticipated significant shift in the role of biomass within the future energy system, it is necessary to consider substantially shorter evaluation periods in this context. The ranges of the parameters used are depicted in Table 3.

Table 3. Parameters of sensitivity analysis.

Parameter	Default Value	Range
Interest rate	3%	0–10%
Evaluation period	30 yr	10–50 yr
Price increase	0%	0–10%
Transportation costs	EUR 0.58/(t·km)	EUR 0.20–1.50/(t·km)
Energy costs	100%	30–300% energy price limit

A rising interest rate, especially in concepts where depreciation costs constitute a significant portion of the annuities (concepts with HTC), leads to significantly higher abatement costs. The magnitude of the influence depends on the proportion of depreciation to annual costs, which, in turn, is determined by the ratio of investment costs to ongoing expenses. Overall, the interest rate exerts no significant influence on the ranking of sub-concepts, resulting in low sensitivity overall (see Appendix A, Figure A1).

The evaluation period also affects the results of some concepts. It is evident that, with a duration of 20 years and especially in concepts involving HTC, significant inflection points occur due to necessary reinvestments after the depreciation period. The distribution of concepts remains largely unchanged, indicating that the considered evaluation period does not have a decisive influence on the choice of concepts. With the exception of the aforementioned cases, the evaluation period does not lead to noteworthy changes in the ranking of concepts and is therefore considered not highly sensitive (see Appendix A, Figure A2).

Price increases primarily impact external sludge disposal, making it considerably more expensive. This leads to increased savings compared to the existing system in concepts where sludge is utilized. A price increase has a substantial impact on the ranking of the main concepts but only a minor effect on the ranking of sub-concepts, making it conditionally sensitive (see Appendix A, Figure A3).

Regarding energy costs, it is observed that an increase in these expenses makes concepts with high electricity production or heat generation more economical. However, energy costs do not have a significant impact on the overall results, thus also being conditionally sensitive (see Appendix A, Figure A4).

Transportation costs play a crucial role in concepts where sludge is utilized. In cases of external disposal, transportation constitutes a significant portion of the total costs. Therefore, a reduction in transportation expenses leads to greater savings compared to the existing system. The influence of transportation costs on the overall results is particularly pronounced. Transportation costs have substantial effects on Concept 3 and negligible impacts on other concepts, with no influence on the ranking of sub-concepts, making such costs conditionally sensitive as well (see Appendix A, Figure A5).

Overall, sensitivity analysis reveals that significant changes in the ranking of the main concepts only occur at the edges of the parameter ranges, and these mostly affect the sub-concepts within a given concept. Therefore, the examined parameters are classified as slightly sensitive for comparing the concepts with each other.

4. Discussion

This manuscript delineates a systematic approach for the comprehensive integration of biogenic resources across diverse sectors. Functioning as a nexus, this approach establishes a collaborative framework involving both private and public stakeholders within waste management, wastewater management, and agricultural domains, which are recognized as potential contributors to the biogenic resources essential for energy generation. This paper provides an exhaustive and foundational elucidation of the procedural steps a rural municipality should undertake to harness biogenic resources for energy production in rural environments.

Employing an iterative strategy, the methodology's development underwent recurrent cycles of inventory analysis, potential analysis, conceptualization, and concept evaluation. This iterative design unfolded in tandem with the active engagement of local stakeholders representing the pertinent sectors. Key figures, including the mayor, local energy manager, and representatives from industrial and civil sectors, participated in a collaborative fashion. This approach facilitated the development of a pragmatic methodology.

Crucially, the conceptualization phase remained an ongoing consultative process with local stakeholders to ensure that the continuous results aligned with real-world implementability. This proactive engagement sought to validate the viability and feasibility of the proposed methodology within the temporal constraints of practical application.

By focusing on the interconnected dynamics of waste management, wastewater management, and agriculture, this study selectively delves into a particular facet and a designated option space pertinent to energy transition. As a consequence, no deliberate juxtaposition or assessment is made vis à vis with alternative sustainable energy supply concepts. Nevertheless, it is imperative to recognize that the outlined methodology possesses the versatility to be incorporated into a more comprehensive and holistic perspective. Notably, industrial biomass (e.g., from breweries) or forestry biomass is not considered as in other approaches (see, e.g., [53,60]) and must be analyzed on a case-by-case basis. On the other hand, the energy potential of wastewater and its partial material flows are rarely integrated in biomass investigations combining more than two sectors (see, e.g., [61]). This study, therefore, provides a new type of added value for research into the energetic utilization of biogenic resources.

The scope of this study demarcates the spatial confines within which the analyses and conceptual frameworks were tailored. Consequently, the exploration overlooked potentially synergistic biogenic resources from neighboring areas that could amplify the efficacy of the investigated concepts. Importantly, the formulated concepts are elaborated for three distinct target settings within the study domains. Any extension of these investigations to alternative study areas necessitates a bespoke adaptation, as there exists no universal "recipe" applicable to all locales. Rather, the configuration of technology options (and their combinations) must be individually modeled to ascertain their efficacy in achieving specific objectives.

However, the developed methodology remains highly replicable in rural settings, with the exception of noted limitations and location-specific considerations. The used calculations and values were derived from the recognized technical rules of the sectors involved in this study and were verified with the specific stakeholders in the study area. Furthermore, methodological and technical focal points were discussed and defined jointly in workshops.

Implementing the developed methodology yielded reliable results within the study area. The three core concepts, along with their sub-concepts, which were collaboratively crafted with local stakeholders, contribute positively to both climate protection and local heat supply. This underscores the effectiveness of interconnecting waste management, wastewater management, and agriculture to generate pertinent energy solutions.

Notably, the obtained outcomes prompted immediate efforts from local stakeholders to realize Concept 3. However, discussions with local stakeholders and experts affirmed the desirability of a combined approach involving all three core concepts. The study area's generic structure for rural municipalities enhances the potential for widespread applicability. As the study area consists of 19 municipal districts, the findings also hold significance for inter-municipal cooperation in diverse local settings.

To advance the scientific evolution of the research findings, dynamic exploration is warranted. This entails various analyses, e.g., analyzing the impact of changing population figures on the achieved results. Additionally, there is a need for addressing unresolved issues surrounding legal implementation and financial management for local stakeholders. Given the ongoing transformation of the institutional framework for energy concepts, the role of biomass in local energy generation requires continuous scrutiny in future studies.

Applying the presented approach should be supported by adjusting policies at the local and national levels. At the local level, the paradigm of the cross-sectoral management of biogenic residues should be incorporated into municipal statutes and administrative guidelines to initialize a shift from predominant sectoral management solutions toward energy-optimized approaches based on combinations of biogenic residues of different sectors. Furthermore, to be able to implement each identified sub-concept, adjustments of national policies are needed. The current institutional framework is not aligned with the aim of the systematic usage of local residues for energy production and the implementation of corresponding concepts. For example, from an operator's perspective, it is almost impossible to secure the (long-term) procurement of local residues due to competitive tendering requirements under the law, which makes investing in approaches to utilize local residues considerably more difficult.

5. Conclusions

The transition toward sustainable energy systems requires a more efficient use of energy and the systematic coupling of different energy sources from various sectors. From a socio-economic perspective, a transition and future energy supply at the municipal level needs to be affordable, consumer-friendly, efficient, and environmentally friendly. In order to pursue energy transition, urban and rural municipalities are challenged with designing Communal Energy Plans describing their long-term perspective on heat supply. In comparison to renewable energy sources such as solar power, wind energy, and geothermal heat, the systematic coupling of biogenic residues from waste, agriculture, and wastewater sectors for energy production has barely been considered by community decision makers until now. Aiming to support the design of suitable energy systems for rural areas, this paper outlines a systematic approach consisting of four steps, starting from an in-depth analysis of local technical and biogenic aspects to the conceptualization and evaluation of potential energy concepts. The presented approach supports decision makers to systematically investigate the local energy potential of biogenic residues from waste, agriculture, and wastewater management and define the energy concepts suitable for the local conditions. While it can be assumed that most municipalities rely on other sources of energy to meet their energy demand, biogenic residues can be considered a relevant component of the transition toward locally based, diversified, and climate-friendly energy systems.

Author Contributions: Conceptualization, A.L., M.W. and M.P.; methodology, M.P.; formal analysis, M.P.; investigation, M.W., A.L. and M.P.; data curation, M.P.; writing—original draft preparation, M.P., A.L. and M.W.; writing—review and editing, E.K. and C.V.; visualization, M.P. and A.L.; supervision, E.K. and C.V.; project administration, E.K.; funding acquisition, A.L. and C.V. All authors have read and agreed to the published version of the manuscript.

Funding: The research for this paper was part of the project OLE (Organisation ländlicher Energiekonzepte/organizing rural energy concepts), which is financially supported by the German Federal Ministry of Education and Research (BMBF) within the measure "Kommunen Innovativ" (grant number: 033L229).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

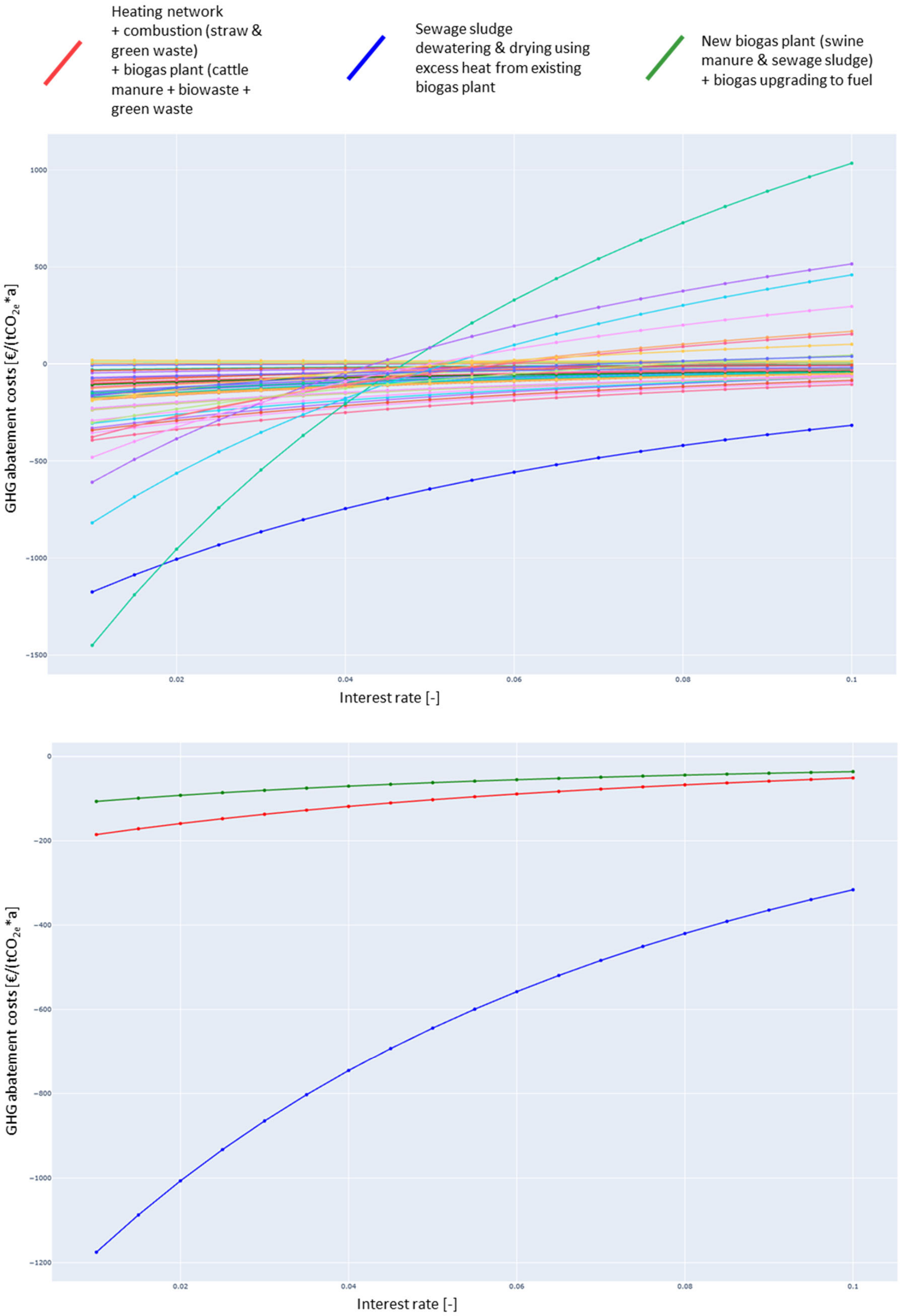

Figure A1. Interest rate in the sensitivity analysis.

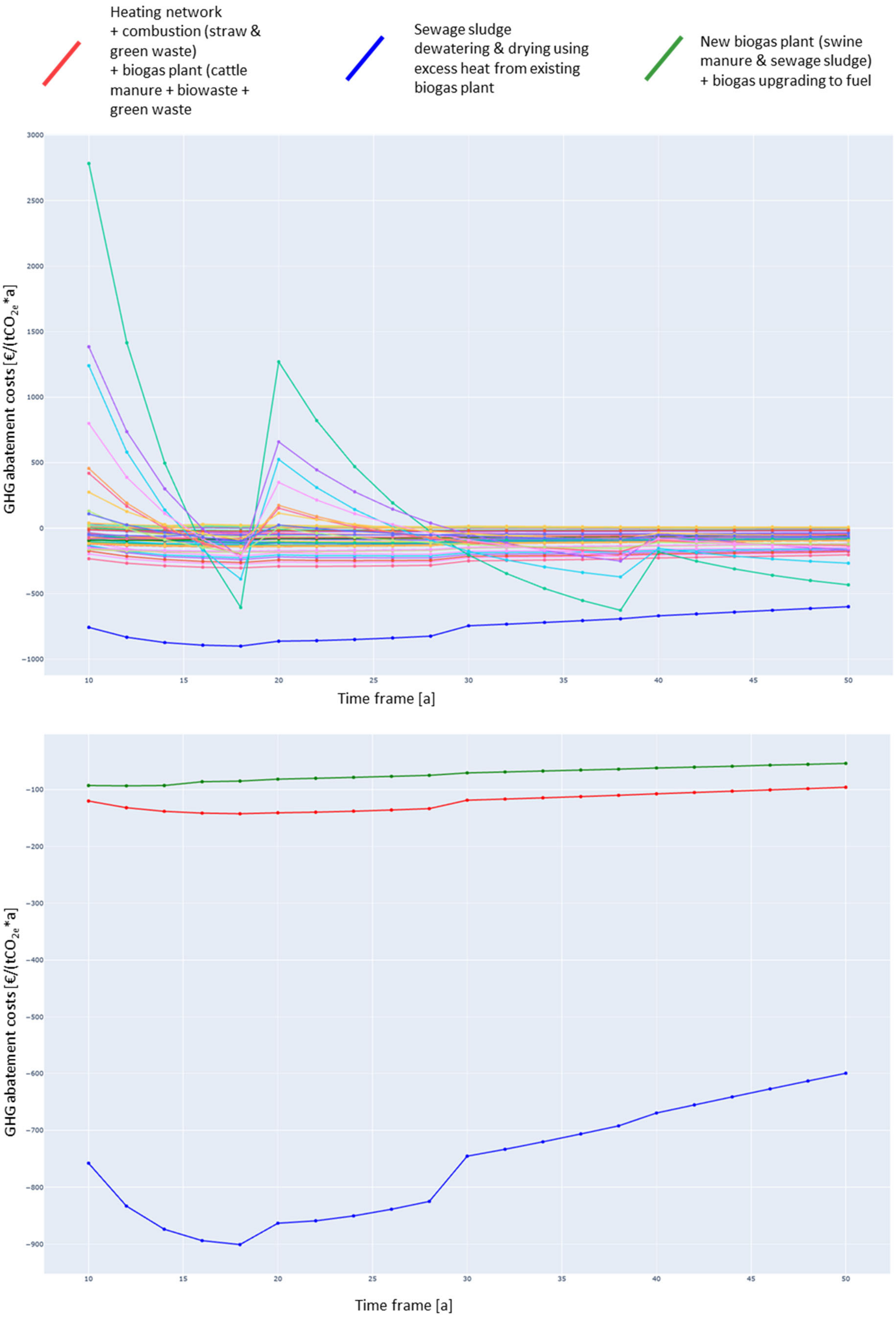

Figure A2. Time frame of the sensitivity analysis.

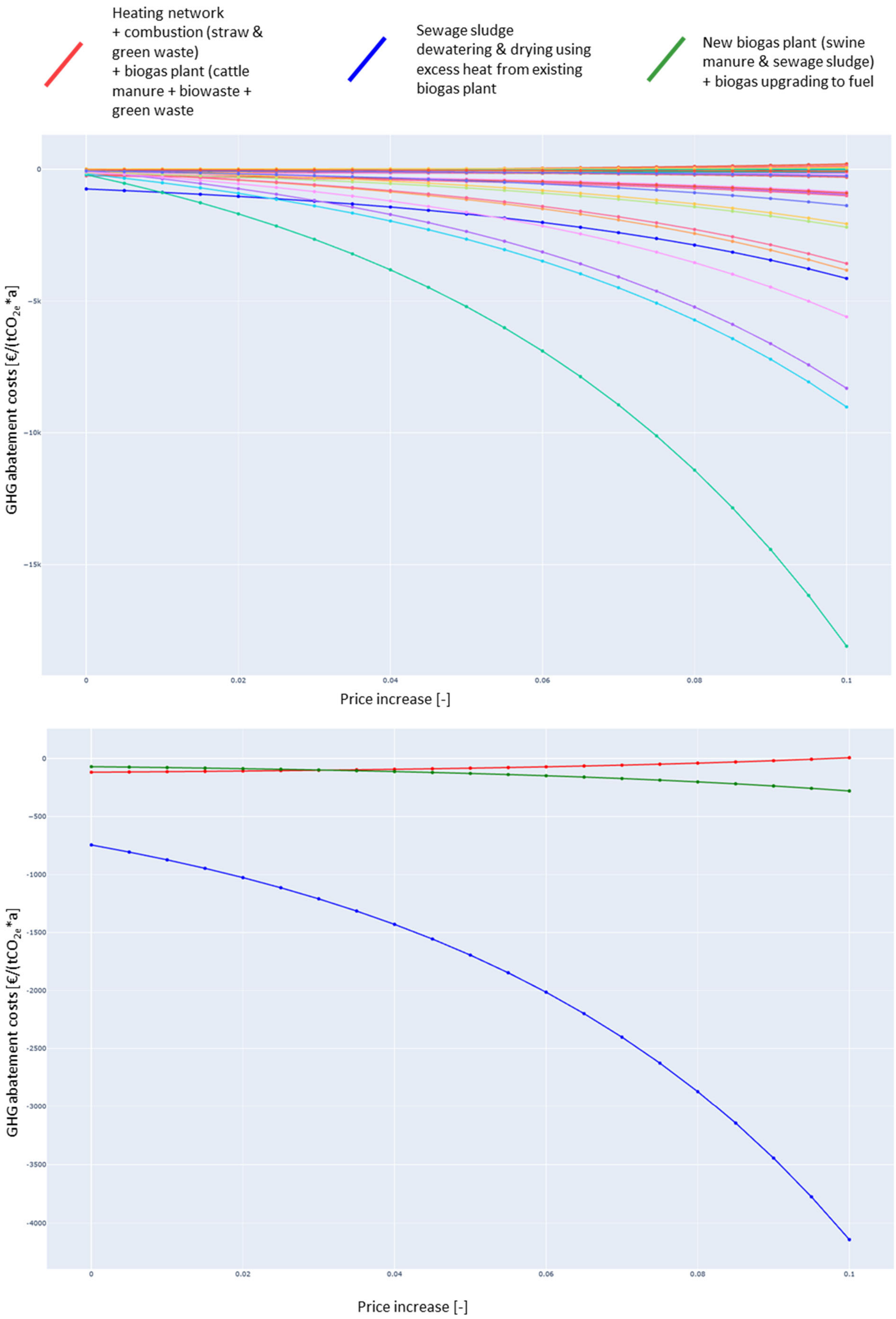

Figure A3. Price increase in the sensitivity analysis.

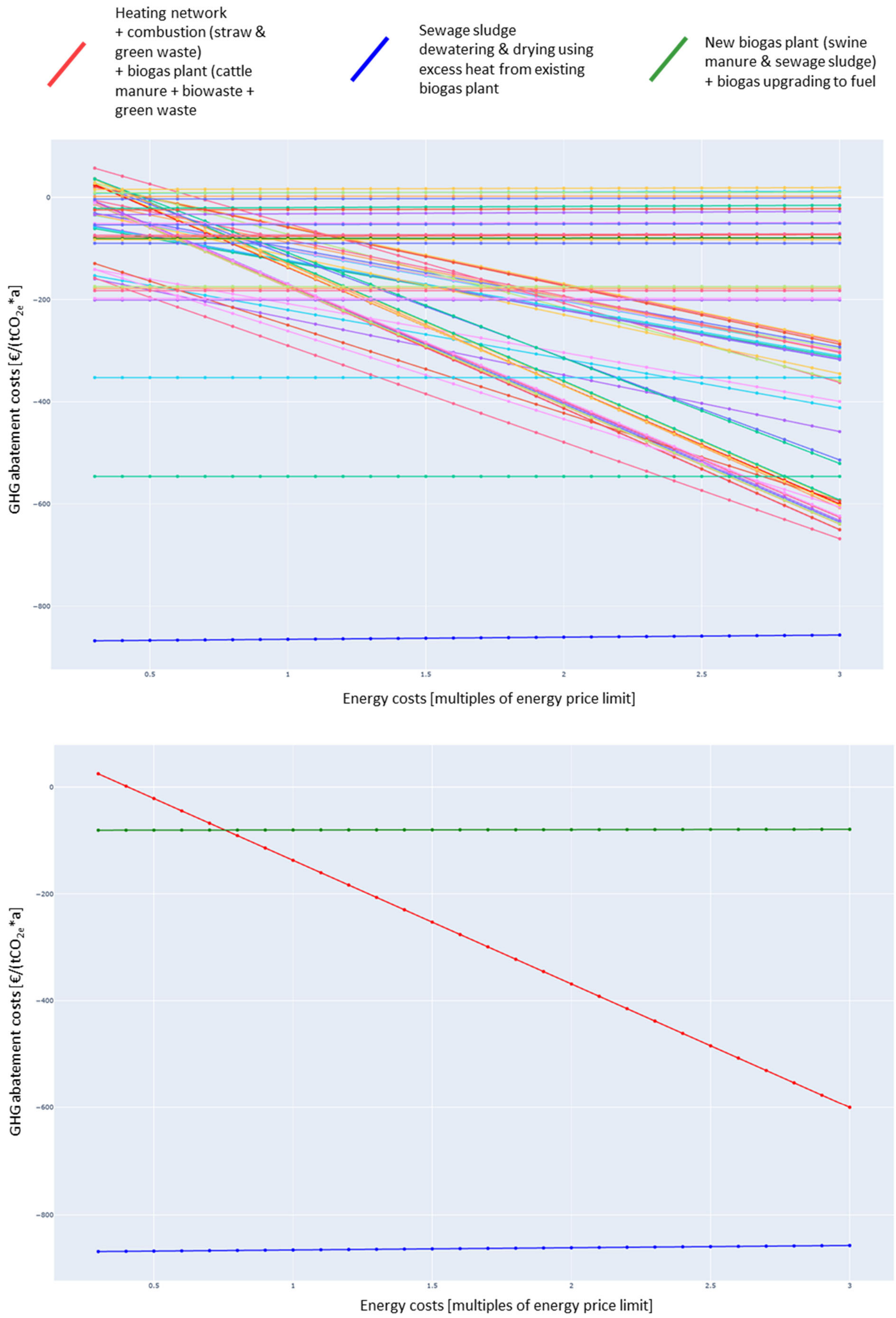

Figure A4. Energy costs in the sensitivity analysis.

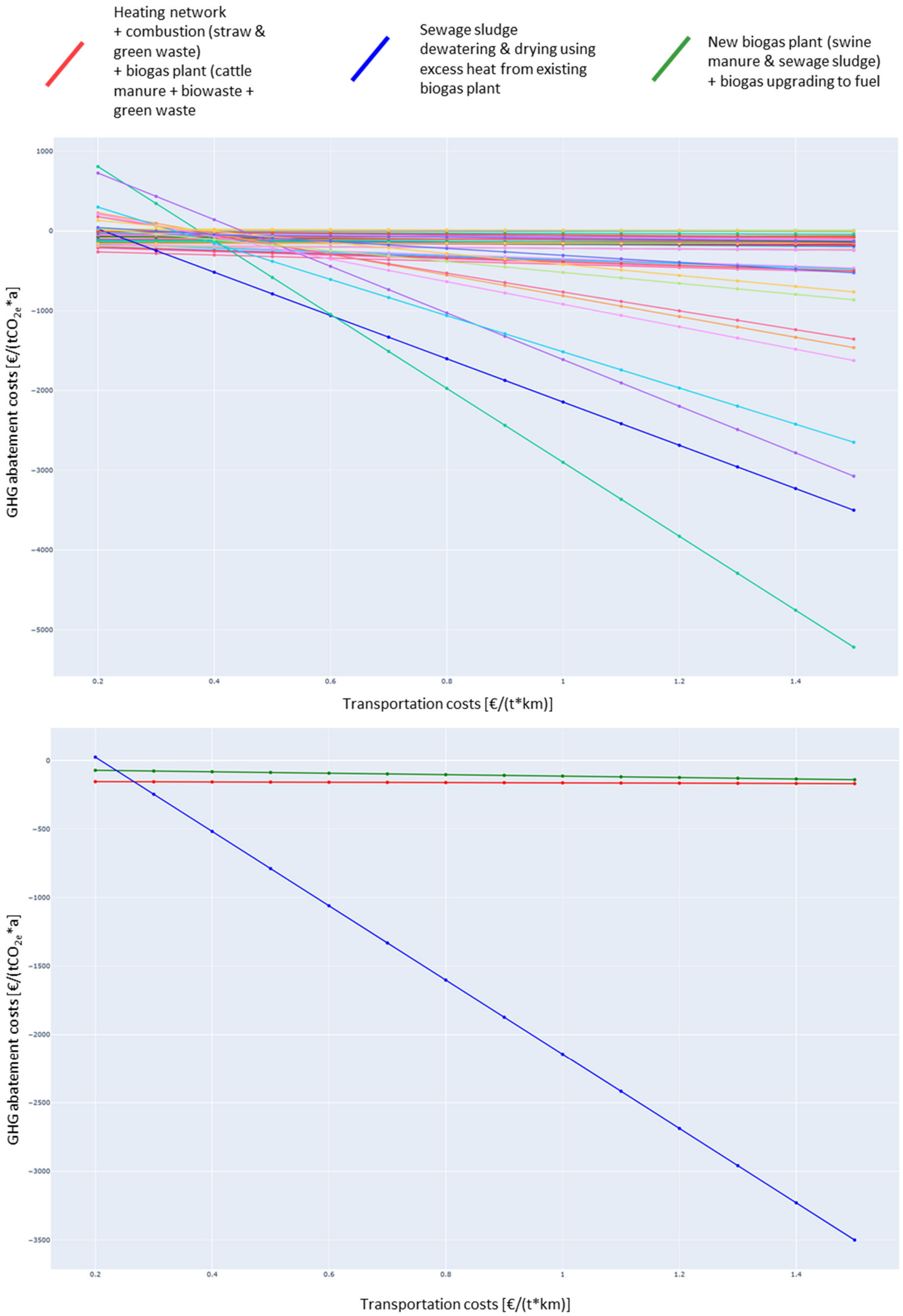

Figure A5. Transportation costs in the sensitivity analysis.

References

1. United Nations. *Transforming Our World: The 2030 Agenda for Sustainable Development*; United Nations: New York, NY, USA, 2015.
2. Bundesministerium für Bildung und Forschung-BMBF Innovation & Strukturwandel, Strom und Wärme Durch Wasserstoff. 2021. Available online: https://www.innovation-strukturwandel.de/strukturwandel/de/report/_documents/artikel/r-t/strom-und-waerme-durch-wasserstoff.html (accessed on 27 November 2023).
3. Kurz, R.; Brun, K. Gas Turbine Performance. In *Asia Turbomachinery & Pump Symposium*; Turbomachinery Laboratories, Texas A&M Engineering Experiment Station: College Station, TX, USA, 2016. [CrossRef]
4. Shourangiz-Haghighi, A.; Diazd, M.; Zhang, Y.; Li, J.; Yuan, Y.; Faraji, R.; Ding, L.; Guerrero, J.M. Developing More Efficient Wind Turbines: A Survey of Control Challenges and Opportunities. *IEEE Ind. Electron. Mag.* **2020**, *14*, 53–64. [CrossRef]
5. Florescu, A.; Barabas, S.; Dobrescu, T. Research on Increasing the Performance of Wind Power Plants for Sustainable Development. *Sustainability* **2019**, *11*, 1266. [CrossRef]
6. Parthiban, R.; Ponnambalam, P. An Enhancement of the Solar Panel Efficiency: A Comprehensive Review. *Front. Energy Res.* **2022**, *10*, 937155. [CrossRef]
7. Dhilipan, J.; Vijayalakshmi, N.; Shanmugam, D.B.; Jai Ganesh, R.; Kodeeswaran, S.; Muralidharan, S. Performance and efficiency of different types of solar cell material—A review. *Mater. Today Proc.* **2022**, *66*, 1295–1302. [CrossRef]
8. Energy Institute. *Statistical Review of World Energy*; Energy Institute: London, UK, 2023.
9. United Nations. *The Sustainable Development Goals Report 2023*; United Nations: New York, NY, USA, 2023.
10. Lachal, B. *Energy Transition*; ISTE Ltd.: London, UK; John Wiley and Sons Inc.: London, UK, 2019.
11. Cajot, S.; Peter, M.; Bahu, J.-M.; Guignet, F.; Koch, A.; Maréchal, F. Obstacles in energy planning at the urban scale. *Sustain. Cities Soc.* **2017**, *30*, 223–236. [CrossRef]
12. Sperling, K.; Hvelplund, F.; Mathiesen, B.V. Centralisation and decentralisation in strategic municipal energy planning in Denmark. *Energy Policy* **2011**, *39*, 1338–1351. [CrossRef]
13. Brugmann, J. Planning for sustainability at the local government level. *Environ. Impact Assess. Rev.* **1996**, *16*, 363–379. [CrossRef]
14. Hoppe, T.; Miedema, M. A Governance Approach to Regional Energy Transition: Meaning, Conceptualization and Practice. *Sustainability* **2020**, *12*, 915. [CrossRef]
15. Poggi, F.; Firmino, A.; Amado, M. Planning renewable energy in rural areas: Impacts on occupation and land use. *Energy* **2018**, *155*, 630–640. [CrossRef]
16. Marsden, T. Exploring the Rural Eco-Economy: Beyond Neoliberalism. *Sociol. Rural.* **2016**, *56*, 597–615. [CrossRef]
17. Wagner, O.; Thomas, S. Wärmewende darf nicht zu Lasten der Armen gehen. Die Wärmewende durch kommunale Wärmeplanung sozial gestalten. *Kommunale* **2023**, *20*, 12–13.
18. Energieeffizienzverband für Wärme, Kälte und KWK e.V.; Deutscher Verein des Gas-und Wasserfaches e.V. Praxisleitfaden: Kommunale Wärmeplanung, Frankfurt/Bonn, Germany. 2023. Available online: https://www.dvgw.de/medien/dvgw/leistungen/publikationen/leitfaden-kommunale-waermeplanung-dvgw-agfw.pdf (accessed on 5 November 2023).
19. Eurostat. *Eurostat Regional Yearbook 2019*; Publications Office of the European Union: Luxembourg, 2019.
20. Naumann, M.; Rudolph, D. Conceptualizing rural energy transitions: Energizing rural studies, ruralizing energy research. *J. Rural. Stud.* **2020**, *73*, 97–104. [CrossRef]
21. Woods, M. Rural geography III. *Prog. Hum. Geogr.* **2012**, *36*, 125–134. [CrossRef]
22. Markantoni, M.; Woolvin, M. The role of rural communities in the transition to a low-carbon Scotland: A review. *Local Environ.* **2015**, *20*, 202–219. [CrossRef]
23. Gregg, J.S.; Smith, S.J. Global and regional potential for bioenergy from agricultural and forestry residue biomass. *Mitig. Adapt. Strateg. Glob. Change* **2010**, *15*, 241–262. [CrossRef]
24. Singh, A.K.; Pal, P.; Rathore, S.S.; Sahoo, U.K.; Sarangi, P.K.; Prus, P.; Dziekański, P. Sustainable Utilization of Biowaste Resources for Biogas Production to Meet Rural Bioenergy Requirements. *Energies* **2023**, *16*, 5409. [CrossRef]
25. Lueck, A.; Haupt, T.; Kraft, E.; Londong, J. Energetische und Stoffliche Potentiale der Synergetischen Verwertung von Abwasser und Abfall in Thüringen. In Proceedings of the DWA Landesverbandstagung Sachsen/Thüringen, Leipzig, Germany, 9 June 2019.
26. Kalcher, J.; Naegeli de Torres, F.; Gareis, E.; Cyffka, K.-F.; Brosowski, A. *Dashboard Biogene Rohstoffe in Deutschland*; Open Agrar Repositorium: Greifswald, Germany, 2022.
27. Ramirez Camargo, L.; Stoeglehner, G. Spatiotemporal modelling for integrated spatial and energy planning. *Energy Sustain. Soc.* **2018**, *8*, 32. [CrossRef]
28. Müller, M.; Kubli, M.; Ulli-Beer, S. Interdisciplinary Modeling of Energy Transition in Rural and Urban Systems. In Proceedings of the International Conference CISBAT 2015, Lausanne, Switzerland, 9–11 September 2015.
29. Naumann, M.; Reichert-Schick, A. Ländliche Infrastrukturen–Risiken, Anpassungserfordernisse und Handlungsoptionen. *Raumforsch. Raumordn.* **2015**, *73*, 1–3. [CrossRef]
30. Thüringer Ministerium für Infrastruktur und Landwirtschaft. *Demografiebericht_2023: Teil 1: Bevölkerungsentwicklung des Freistaats Thüringen und Seiner Regionen, Erfurt, Germany*. 2023. Available online: https://www.serviceagentur-demografie.de/service/publikationen/demografieberichte/ (accessed on 10 November 2023).
31. © OpenStreetMap Contributors. 2023. Available online: www.openstreetmap.org/copyright (accessed on 29 November 2023).
32. Gemeinde Am Ettersberg. Herzlich Willkommen: Leben Am Ettersberg, das Bedeutet Echte Lebensqualität. Available online: https://www.am-ettersberg.de/ (accessed on 10 November 2023).

33. Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen. Kommunale Wärmeplanung: Für eine Deutschlandweit Zukunftsfeste und Bezahlbare Wärmeversorgung. Available online: https://www.bmwsb.bund.de/Webs/BMWSB/DE/themen/stadt-wohnen/WPG/WPG-node.html (accessed on 10 November 2023).
34. Thüringer Ministerium für Umwelt, Energie und Naturschutz. *Beseitigen von Kommunalem Abwasser in Thüringen: Berichtszeitraum 2021/2022, Erfurt, Germany*. 2023. Available online: https://umwelt.thueringen.de/fileadmin/001_TMUEN/Unsere_Themen/Boden_Wasser_Luft_Laerm/Abwasser/Lageberichte_Abwasserentsorgung/Thueringer_Lagebericht_Kommunalawasser_2023_01.pdf (accessed on 5 November 2023).
35. Wolf, M.; Londong, J. Transformation der Siedlungswasserwirtschaft-Steuerungsmechanismen im Diskurs Ressourcenorientierter Systemansätze am Beispiel von Thüringen. *Raumforsch. Raumordn.* **2020**, *78*, 397–411. [CrossRef]
36. Thüringer Landesamt für Landwirtschaft und Ländlichen Raum. *Jahresbericht 2021/22, Jena, Germany*. 2023. Available online: https://tlllr.thueringen.de/fileadmin/TLLLR/Service/Publikationen/Broschueren/2023_JB21.pdf (accessed on 10 November 2023).
37. Thüringer Landesanstalt für Landwirtschaft. *Integration der Biogaserzeugung in die Landwirtschaft in Thüringen: Abschlussbericht*; Thüringer Landesanstalt für Landwirtschaft: Jena, Germany, 2017.
38. Thüringer Landesamt für Landwirtschaft und Ländlichen Raum. Biogas. Available online: https://tlllr.thueringen.de/landwirtschaft/pflanzenproduktion/nawaro/biogas (accessed on 8 November 2023).
39. Schluck, T.; Hangartner, D.; Facchinetti, E.; Sulzer-Worlitschek, S.; Mennel, S.; Sulzer, M. The Uettligen Case—A Step Towards a Role Model in Energy Concept Development. *Energ. Proc.* **2017**, *122*, 1069–1074. [CrossRef]
40. Schluck, T.; Sulzer, M. Towards a Holistic Methodology: A Practical Approach to Local Energy Planning. In Proceedings of the World Sustainable Built Environment Conference 2017, Hong Kong, China, 5–7 June 2017.
41. Berger, K.; Hauer, S.; Peters-Anders, J.; Schmidt, R.-R.; Anna Shadrina, A.; Widl, E.E. *Digitale Energieplanung & Optimierung urbaner Regionen-Herausforderungen, Best-Practice-Beispiele & Handlungsempfehlungen*; Austrian Institute of Technology: Vienna, Austria, 2020.
42. Antoni, O.; Kluge, C.; Knies, J.; Balling, V.; Benz, S.; Schneller, A.; Wegner, N. *Handlungsempfehlungen für ein Planungsmodell der kommunalen Wärmeplanung auf Grundlage Kommunaler Erfahrungswerte und Dessen Rechtlicher Implementierung*; Hochschule Bremen: Bremen, Germany, 2022.
43. Drebes, C.; Meinberg, T.; Schulze, J.; Sieber, S.; Ousmane, S.; Hegger, M.; Dettmar, J. *UrbanReNet II-Weiterentwicklung des Bilanzmodells der Phase I zu einem Quatiersbezogenen Vernetzungsmodell*; Technische-Universität Darmstadt: Darmstadt, Germany, 2015.
44. Caemmerer-Seibel, U.; Kiesel, G.; Voelker, C.; Cebulla, D. Ein online-tool zur Erprobung bezahlbarer Handlungsoptionen für Energieeffizienz im ländlichen Raum. In Proceedings of the BauSIM 2020-8th Conference of IBPSA Germany and Austria, Graz, Austria, 23–25 September 2020.
45. Blesl, M.; Stehle, M.; Brodecki, L.; Groß, P.; Grassl, G.; Reiser, S.; Karajan, J.; Christ, A.; Müller, E. *Systemanalyse für die Städtische Energieplanung mit einem Modularen Planungsinstrument-Methodische Grundlagen und Fallbeispiele*; Endbericht; Universität Stuttgart: Stuttgart, Germany, 2019.
46. Zhang, J.; Qin, Q.; Li, G.; Tseng, C.-H. Sustainable municipal waste management strategies through life cycle assessment method: A review. *J. Environ. Manag.* **2021**, *287*, 112238. [CrossRef]
47. Sarigiannis, D.A.; Handakas, E.J.; Karakitsios, S.P.; Gotti, A. Life cycle assessment of municipal waste management options. *Environ. Res.* **2021**, *193*, 110307. [CrossRef]
48. Hörnschemeyer, B.; Söfker-Rieniets, A.; Niesten, J.; Arendt, R.; Kleckers, J.; Stretz, C.; Klemm, C.; Budde, J.; Wagner, R.; Vonhoegen, L.; et al. *Leitfaden RessourcenPlan–Teil 1: Konzeption RessourcenPlan. Ergebnisse des Projekts R2Q RessourcenPlan im Quartier*; Fachhochschule Münster: Münster, Germany, 2023.
49. Caemmerer-Seibel, U.; Lück, A.; Osman, A.; Kiesel, G.; Völker, C.; Alfen, H.W.; Cebulla, D. Energy Transition in Rural Areas–Supporting Local Energy Planning by the Development of an Online-Tool for Identification and Promotion of Energy-Efficiency and the Use of Renewables. In Proceedings of the Building Simulation 2019-16th Conference of IBPSA, Rome, Italy, 2–4 September 2019.
50. Statistische Ämter des Bundes und der Länder. ZENSUS 2011. Available online: https://www.zensus2011.de (accessed on 10 November 2023).
51. Thüringer Landesamt für Vermessung. Thüringer ALKIS®-Objektartenkatalog: Auf Basis der GeoInfoDok Version 6.0.1. Available online: https://www.thueringen.de/mam/th9/tlvermgeo/landesamt/thuralkis-ok.pdf (accessed on 7 January 2022).
52. Gesellschaft für Energieplanung und Systemplanung mbH. *Verbrauchskennwerte 2015*; Gesellschaft für Energieplanung und Systemplanung mbH: Münster, Germany, 2015.
53. Yang, L.; Wang, X.-C.; Dai, M.; Chen, B.; Qiao, Y.; Deng, H.; Zhang, D.; Zhang, Y.; Villas Bôas de Almeida, C.M.; Chiu, A.S.; et al. Shifting from fossil-based economy to bio-based economy: Status quo, challenges, and prospects. *Energy* **2021**, *228*, 120533. [CrossRef]
54. German Association for Water Management, Sewage and Waste e. v. *Leitlinien zur Durchführung Dynamischer Kostenvergleichsrechnungen (KVR-Leitlinien)*; German Association for Water Management, Sewage and Waste e.v.: Hennef, Germany, 2012.
55. Thüringer Landesamt für Umwelt und Geologie. *Ergebnisse der Hausmüllanalysen der Öffentlich-Rechtlichen Entsorgungsträger im Zeitraum 2011–2017: Kompostierbare Abfälle*; Thüringer Landesamt für Umwelt und Geologie: Jena, Germany, 2018.

56. Thüringer Landesamt für Statistik. *Energiebilanz Thüringen 2020*; Thüringer Landesamt für Statistik: Erfurt, Germany, 2022.
57. Kaltschmitt, M.; Hartmann, H.; Hofbauer, H. *Energie aus Biomasse*, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2016.
58. Bulach, W.; Dehoust, G.; Möck, A.; Oetjen-Dehne, R.; Kaiser, F.; Radermacher, J.; Lichtl, M. *Ermittlung von Kriterien für Hochwertige Anderweitige Verwertungsmöglichkeiten von Bioabfällen*; Umweltbundesamt: Dessau-Rosslau, Germany, 2020.
59. Kern, M.; Raussen, T.; Funda, K.; Lootsma, A.; Hofmann, H. *Aufwand und Nutzen einer Optimierten Bioabfallverwertung Hinsichtlich Energieeffizienz, Klima-und Ressourcenschutz*; Umweltbundesamt: Dessau-Roßlau, Germany, 2010.
60. Long, H.; Li, X.; Wang, H.; Jia, J. Biomass resources and their bioenergy potential estimation: A review. *Renew. Sustain. Energy Rev.* **2013**, *26*, 344–352. [CrossRef]
61. Iqbal, A.; Ekama, G.A.; Zan, F.; Liu, F.X.; Chui, H.-K.; Chen, G.-H. Potential for co-disposal and treatment of food waste with sewage: A plant-wide steady-state model evaluation. *Water Res.* **2020**, *184*, 116175. [CrossRef]