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Digesters as Heat Storage – Energetic Assessment of Flexible Variation of Digester Temperature

A flexible digester temperature enables holistic storage of surplus heat and minimization of heat deficits on water resource recovery facilities (WRRFs). Heat-saving potentials, performance as heat storage, and emissions of CO_2 are considered in four scenarios with increasing flexibility of digester temperature for a model WRRF with 500 000 PE (population equivalent). In comparison to a digester temperature at 37 °C all year, the scenario with seasonal variation of average digester temperatures between 32.5 and 43.6 °C has the greatest annual heat-saving potential and increase of stored heat. Further, the ranges of digester temperatures indicate a great performance as heat storage.

Keywords: Anaerobic digesters, Digester temperature, Heat balances, Heat storage, Water resource recovery facilities

Received: May 29, 2021; *revised:* September 21, 2021; *accepted:* November 15, 2021

DOI: 10.1002/ceat.202100240

1 Introduction

Digesters are key components of a holistic heat management at water resource recovery facilities (WRRFs) acting both as heat consumers and indirectly as heat generators due to heat supply from usage of biogas in combined heat and power (CHP) units. With progressive optimization of energy efficiency and modern heat-consuming process steps (e.g., hygienization, thermal disintegration, sludge drying, deammonification or cooling), holistic heat management is becoming more and more important at WRRFs.

As there still is a focus on electricity consumption and supply, heat plays an important role at WRRFs in Germany as heat supply and demand are quantified to 1.1 and 3.2 $TWh_{th}a^{-1}$, while electricity supply and demand are on the same scale with 1.1 and 4.2 $TWh_{th}a^{-1}$ [1]. Further, specific electricity demand and supply can be amount to 32.6 and 19.8 $kWh_{el}PE^{-1}a^{-1}$ (PE denotes population equivalent) for WRRFs in Germany [2], while equivalent data focusing on heat demand and supply is rare. For WRRFs with digesters and usage of biogas, specific thermal supply and demand of 20–40 $kWh_{th}PE^{-1}a^{-1}$ and 0–30 $kWh_{th}PE^{-1}a^{-1}$ are estimated [3].

Considering the digester temperature at WRRFs, digesters usually operate at constant temperature levels mostly at mesophilic levels between 30 and 40 °C, usually around at 37 °C, and sporadically at thermophilic temperatures between 50 and 55 °C [4–7]. Due to constant digester temperatures through the year, the heat demand of WRRFs typically changes because of seasonal variation of raw sludge and air temperature causing phases of heat deficits in winter and surplus heat in summer months (cf. Fig. 2, scenario I).

As there are rarely neither heat storages nor access to heat networks, surplus heat either has to be used by further heat consumers or converted in emergency coolers with additional energy input. At the same time, heat supply mainly depends on the quality of the raw sludge fed to digesters as well as the stability of an anaerobic degradation process. Thus, the time lag of phases with heat deficit and surplus heat indicates great potential to store surplus heat and provide it when needed at a later time. As digesters are already an essential part of heat management at WRRFs, using them for anaerobic stabilization and as heat storage is an obvious approach. From an energetic point of view, motivation for dynamic adjustment of digester temperatures is seasonal compensation of heat demand and holistic heat usage onsite along with low emissions of CO_2.

Using digesters as seasonal heat storage is implemented by increasing the digester temperature in summer with excessive heat and decreasing the digester temperature in winter when heat demand exceeds heat supply [7]. Adapting the digester temperature in dependence on available heat within WRRFs and thus using digesters as heat storage is recommended up to 40 and 42 °C, whereby increasing temperatures require static proof especially of concrete digesters [7, 8]. Although, there is a lack of information in literature describing the performance of digesters as heat storage with suitable parameters. Variation of

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seasonal digester temperatures between 33 and 53 °C is described for two WRRFs in Germany [9] and between 38 and 52 °C for a WRRF in Austria [10] indicating no inactivation of bacteria producing methane at temperatures between mesophilic and thermophilic conditions.

However, anaerobic degradation between 30 and 60 °C is considered in several publications focusing on sewage sludge [11–14] as well as residual, agricultural, and waste material [15–18] fed to fermenters describing stable anaerobic degradation between meso- and thermophilic temperatures as long as temperature changes are kept to a minimum. For WRRFs, temperature changes below 0.5–2.5 K per day [5, 19, 20] and 2–5 K per week [7, 21] are recommended to maintain stable anaerobic process conditions whereby already short-term temperature changes can cause process disturbances [20, 22, 23].

Systematic, detailed information about heat demand and supply can be provided by heat balances following calculations recommended in [8, 24]. Here, the heat demand is divided into compensation of transmission, tempering of raw sludge to digester temperature, hot water and heating of operation buildings as well as conversion, storage, and distribution losses. Heat supply remains constant through the year. Additional site-specific heat consumers such as hygienization, thermal disintegration, sludge drying, deammonification or cooling are not outlined separately. Heat supply is based on production of methane-rich biogas converted into electricity and heat within CHP units. A heat balance is demonstrated in detail for a municipal model WRRF with 500 000 PE for constant digester temperature at 35 °C all year [8]. Assuming moderate climate conditions, phases of heat deficit and surplus heat occur due to seasonal variation in raw sludge and air temperature.

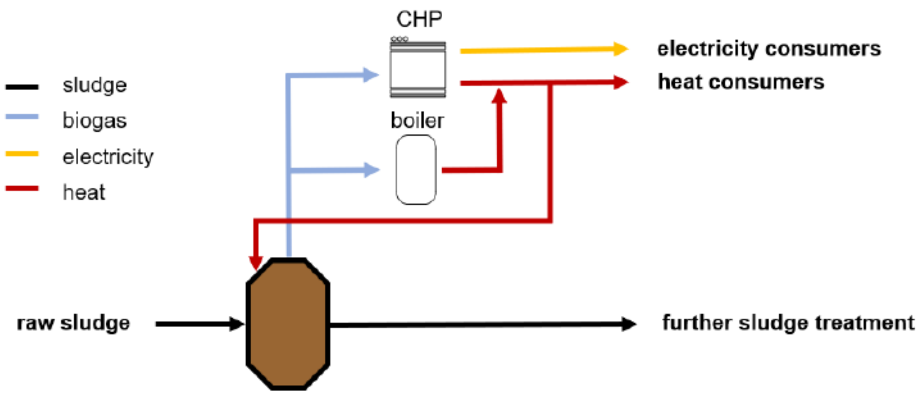

Figure 1. Key components of heat balances and energy flow diagrams showing the inner flows of sludge, biogas, electricity, and heat. For heat balances, biogas is only used in the CHP unit and losses are calculated only for the digester as additional heat demand due to residual heat in sludge and biogas leaving the digester; for energy flow diagrams, biogas is partly used in the CHP unit and boiler and losses are calculated for the components digester, CHP unit, and boiler separately.

Aim of this paper is to evaluate heat-saving potentials and performance as heat storage of digesters in different scenarios of flexible digester temperatures in comparison to state-of-the-art operation strategy of 37 °C through the year.

Table 1. Relevant aspects for heat balances focusing on heat supply, heat demand, and storage term for operation strategies with constant and flexible digester temperatures (supply = demand + storage term).

	Supply	Demand	Storage term	
			> 0: surplus heat	< 0: heat deficit
Constant digester temperature	CHP unit/boiler	Transmission, heating up raw sludge, operation buildings/hot water, compensation of residual heat in sludge and biogas	Conversion in emergency coolers	Compensation with boiler
Flexible digester temperature	CHP unit	As above	Heating up digester temperature	Cooling down digester temperature

2 Materials and Methods

The heat balance for a model WRRF with 500 000 PE located in Central Europe is adopted to four scenarios for energetic assessment of varying digester temperatures, following calculations recommended in [8, 25]:

- I – digester temperature at 37 °C (state-of-the-art scenario)
- II – flexible digester temperatures between 37 and 42 °C
- IIa – flexible digester temperatures between 30 and 42 °C
- III – minimum of annual heat deficit and maximum of stored surplus heat with flexible digester temperatures.

Essential components of heat balances and energy flow diagrams are digester, CHP unit, and boiler (Fig. 1). Further, the heat balance is split into heat supply, heat demand, and a storage term indicating if heat is excessive or deficient (Tab. 1). Here, the amount of biogas used in the CHP unit provides the total available heat supply. The total heat demand is divided into compensation of heat losses due to transmission, heating up raw sludge as well as heat demand for operation buildings and hot water. Additionally, compensation of losses due to residual heat in sludge and biogas with regard to temperature level of raw sludge is considered in heat demand and loss of the digester [25]. Further, underlying parameters represent a thermally optimized WRRF (e.g., for transmission coefficient, specific heat demands, efficiencies) according to the state of the art (Tab. 2).

Taking into consideration the results of data evaluation of WRRFs with variation of digester temperatures between 33 and 53 °C, specific methane yields are set constant at all considered

Table 2. Calculation basis for heat balances and energy flow diagrams.

Aspect	Parameter	Value
Design of WRRF	Population equivalent [PE]	500 000
Design of digester	Hydraulic retention time [d]	20.0
	Volume digester [m^3]	16 000
	Heat transition coefficient [$W\,m^{-2}K^{-1}$]	0.3
	Degradation of COD [%][a]	65.0
	Electricity demand based on raw sludge [$kWh_{el}m^{-3}$]	1.95[b]
Heating of sludge	Specific amount of raw sludge [$g_{TS}\,PE^{-1}d^{-1}$]	60.0
	Amount of raw sludge [m^3a^{-1}]	219 000
	TS of raw sludge [%]	5.0
	TVS of raw sludge [%]	73.0
	Specific heat capacity [$kWh_{th}m^{-3}K^{-1}$]	1.16[c]
Operation building	Specific heat demand [$kWh_{th}m^{-2}a^{-1}$]	150.0
	Area of operation buildings [m^2]	5000
Hot water	Demand for hot water [m^3a^{-1}]	10 000
	Thermal efficiency of heat exchanger [%]	95.0
	Temperature of unheated water [°C]	10.0
	Temperature of heated water [°C]	75.0
Pathway of gas	Specific gas yield [$L_Nkg_{VS,added}{}^{-1}$]	500.0
	Methane content [%]	63.0
	Thermal efficiency of CHP unit [%]	53.0
	Calorific value of methane [$kWh\,m_{N,CH4}{}^{-3}$]	10.0
	Thermal efficiency of boiler [%]	95.0

[a] As average of degradation of COD reported in [9, 11, 12, 13]. [b] [8]. [c] Equivalent for water and raw sludge.

temperature levels and the methane content of biogas is set to 63 % [9]. Further, heat balances follow these aspects:

- Biogas is only employed in the CHP unit neither buffered in gas storage nor used in boilers.
- Digester temperatures are considered as monthly average. Variation of temperature only occurs when heat deficit or surplus heat per month is present. While surplus heat is stored in form of increased digester temperature, heat deficit results in cooling down.
- While heating up the digester temperature is achieved by heating up raw sludge to a higher temperature level, cooling down is traced back to temporarily suspended compensating of heat losses due to transmission and residual heat in sludge and biogas.
- Heat demand for operation buildings only occurs within the heating period between October and April in Central Europe. The demand of hot water is constant all year.

Based on the results of the heat balances, energy flow diagrams visualize a detailed view on annual flows focusing on the heating system of the digester. All flows are quantified as $Wh\,kg_{COD}{}^{-1}$ (COD = chemical oxygen demand) and are based on the annual COD load of 12 070 $Mg_{COD}\,a^{-1}$ in raw sludge (calculated with values in Tab. 2). Energy potential is calculated based on 1 kg_{COD} equals 3.2 kWh with a ratio of COD/VS (VS = volatile solids) of 1.51 for raw sludge [26, 27]. Input parameter is raw sludge, while the output flow is divided into digested sludge, available electricity and heat for further consumers as well as losses due to energy conversion, residual heat, and transmission.

In contrast to the approach of heat balances, a boiler compensates heat deficits to the extent needed by reducing biogas used in the CHP unit. Thus, recalculation of the gas flow used in the CHP unit and boiler with different thermal efficiencies is necessary to meet the total heat demand. Here, heat consumers summarize the heat demand for hot water and operation buildings as well as available surplus heat.

In addition to the energy flow diagrams, emission equivalents of CO_2 (CO_2-eq) are estimated for each scenario with the following assumptions:

- Usage of biogas in the CHP unit and boiler causes air emissions. Calculations consider 26.2 $g_{CO2}kWh_{el}{}^{-1}$ and 14.9 $g_{CO2}kWh_{th}{}^{-1}$ for electricity and heat supply from biogas in the CHP unit and only for heat supply from biogas in boilers [28].
- Annual heat deficits are compensated with usage of natural gas for heat supply in boilers releasing 248.1 $g_{CO2}kWh_{th}{}^{-1}$ [28]. Annual heat surplus has to be converted in emergency coolers with additional electricity demand met by supply from a public power grid (401.0 $g_{CO2}kWh_{el}{}^{-1}$ for the average electricity mix in Germany for 2019) [29].
- Further, the more biogas is used in the CHP unit, the higher is the electricity supply onsite. Thus, the reference value is the electricity supply in scenario I resulting in the need to feed or purchase electricity from a public power grid for the others scenarios.

3 Results and Discussion

3.1 Quantification of Heat Deficit and Surplus Heat

From an energetic point of view, phases of heat deficit and surplus heat can be used for cooling down or heating up the digester temperature. Whether deficient or surplus heat occurs, depends on the difference between digester and raw sludge temperature as heating up raw sludge is the main heat consumer. Additionally, aspects such as design of digesters (geometry, heat transition coefficient), daily amount of raw sludge, specific heat demand for operation buildings and hot water as well as thermal efficiency of the CHP unit show an additional impact resulting in variations of monthly heat demands.

Specific heat demands of 25.2, 27.4, 26.4, and 26.6 $\mathrm{kWh_{th}PE^{-1}a^{-1}}$ are quantified in each scenario whereby around 85 % is needed for increasing the temperature from raw sludge to digester temperature. However, the daily heat supply remains unaffected for all considered scenarios as specific methane yields and methane content are constant at all temperature levels. Slight variations still occur due to different amounts of days per month. In Fig. 2, phases of heat deficit and surplus heat are displayed for increasing flexibility of digester temperature for each scenario.

Conventionally, the digester temperature remains at 37 °C through the year (scenario I). Typically, curves of constant heat supply and seasonal phases of total demand occur. Heat deficits in winter segue into heat surplus as soon as raw sludge and air temperature increase in spring. The maximum heat demand of 1332.3 $\mathrm{MWh_{th}}$ is reached around the turn of the year and is significantly higher than the minimum of 846.6 $\mathrm{MWh_{th}}$ in August. Monthly phases of surplus heat last for two-thirds of a year from April to November.

Digester temperatures between 37.0 and 42.0 °C (scenario II) reduce the phase of surplus heat from July to October. While the digester temperature increases up to 42.0 °C between April and June, cooling down without additional heating starts in September. At the end of December, the digester temperature reaches the initial temperature of 37.0 °C while the average digester temperature in December is 37.8 °C. Total heat deficit amounts to 510.3 $\mathrm{MWh_{th}a^{-1}}$, which is slightly higher than in scenario I due to the higher heat demand for raw sludge heating at increased digester temperatures. In total, the seasonal heat demand is flattened due to the stored amount of surplus heat when the digester temperature increases. During heating-up and cooling-down, the maximum change of the digester temperature is around 2.5 K per month meeting the requirements for process stability recommended in literature [7, 21].

More flexible digester temperatures between 32.5 and 42.0 °C (scenario IIa) lead to further reduction of annual heat deficits. Between January and May, there is a phase of significantly reduced amount of heat deficit in comparison to scenario I showing an annual heat deficit of 49.7 $\mathrm{MWh_{th}a^{-1}}$. In the course of the year, 163.3 $\mathrm{MWh_{th}a^{-1}}$ of surplus heat still remains unused between June and December as scenario IIa is limited to a maximum digester temperature of 42.0 °C. With maximum temperature changes of 3.5 K per month, there are no concerns about maintaining process stability of the anaerobic degradation process. The digester temperature reaches the maximum of 42.0 °C in July and then segues into the cooling phase in September until the end of December when the digester temperature still is around 30.7 °C (average digester temperature in December is 34.7 °C).

Maximum flexibility of the digester temperature is considered in scenario III as the digester temperature completely depends on the amount of available heat deficit and surplus heat each month. Minimum annual heat deficit and surplus heat are achieved with a digester temperature of 32.5 °C in January. Afterwards, the digester temperature increases to a maximum of 43.6 °C in August and thereafter cools down to 34.6 °C in December. At the end of December, the digester temperature is 30.7 °C. Allocated to seasons as shown in scenario I, phases change here to minimum amounts of heat deficit between January and July (40.6 $\mathrm{MWh_{th}}$) and surplus heat between August and December (40.6 $\mathrm{MWh_{th}}$). The total annual sum of surplus heat and heat deficit is 0.0 $\mathrm{MWh_{th}a^{-1}}$. Considerations of using the volume of gas storages are without the scope of the applied approach of heat balances, though might reduce monthly heat deficit and surplus heat to zero.

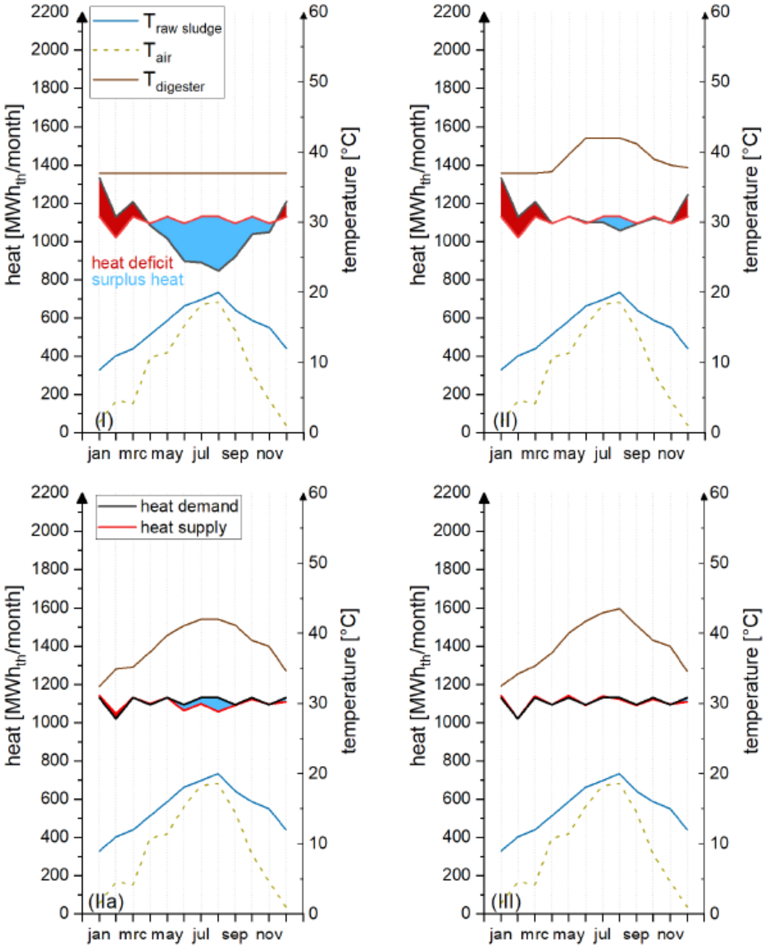

Figure 2. Monthly average of heat demand and supply, temperatures of raw sludge, air, and digester for different operation strategies varying in flexibility of digester temperature in scenarios I, II, IIa, and III.

3.2 Heat-Saving Potentials and Performance as Heat Storage

Considering a holistic heat management at WRRFs, heat deficits should be minimized to avoid compensation by usage of biogas, while surplus heat should be stored by increasing the digester temperature. Therefore, the annual sum of negative (heat deficit) and positive (surplus heat) storage terms from heat balances is considered as heat-saving potential.

Keeping the digester temperature at a constant level in scenario I, the annual heat deficit reaches 465.3 $\mathrm{MWh_{th}a^{-1}}$ and the surplus heat is around 1152.9 $\mathrm{MWh_{th}a^{-1}}$. Due to the time lag between phases of surplus heat and heat deficit, the potential for saving thermal energy amounts to 1618.2 $\mathrm{MWh_{th}a^{-1}}$ (Tab. 3). With increasing flexibility of the digester temperature, the annual sum of deficient and surplus heat can be significantly reduced by 61.4, 86.8, and 95.0 % for scenarios II, IIa, and III. A minimum of surplus heat and heat deficit each with 40.6 $\mathrm{MWh_{th}a^{-1}}$ is reached within scenario III.

For quantification of the amount of stored heat, the temperature of raw sludge is set as reference value. Thus, the amount of heat needed to heat up raw sludge to digester temperature is equivalent to the amount of stored heat. In comparison to scenario I with 5592.4 $\mathrm{MWh_{th}a^{-1}}$, the annual stored heat can be increased by 9.0, 5.0, and 5.9 % for scenarios II, IIa, and III (Tab. 3).

As the temperature of raw sludge is varying between 9 °C in January and 20 °C in August, there is a seasonal trend of stored heat (Fig. 3). With increasing raw sludge temperatures in spring and summer, the amount of stored heat in the digester in scenario I reduces to a minimum in August. In scenario II, the amount of stored heat is the highest in comparison to the other scenarios due to the set digester temperature of 37 °C in the winter months. As the curves for scenario IIa and III are more balanced, the amount of stored heat is higher in summer and lower in winter in comparison to scenario I. Thus, seasonal compensation of heat deficit and surplus heat through the year is reached when the digester temperature is more flexible (scenarios IIa and III).

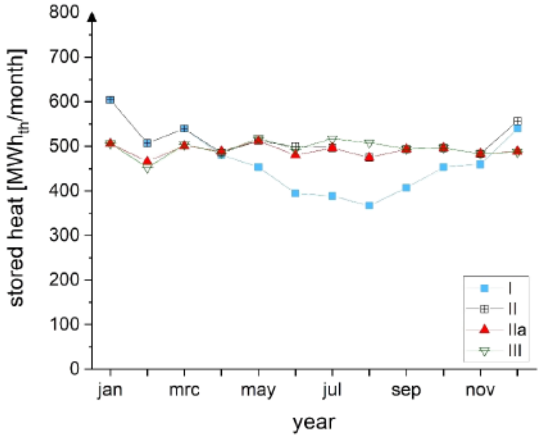

Figure 3. Amount of stored heat in comparison to raw sludge temperature in the course of one year for each scenario.

Table 3. Comparison of scenarios based on data from heat balances regarding annual heat deficit and surplus heat as well as characteristic values for digesters as heat storage.

Aspect	Scenario I	Scenario II	Scenario IIa	Scenario III
Minimum digester temperature [°C][a]	37.0	37.0	32.5	32.5
Maximum digester temperature [°C][a]	37.0	42.0	42.0	43.6
Maximum temperature gradient [$\mathrm{K\ month^{-1}}$]	0.0	2.5	3.5	3.6
Sum of monthly heat deficit [$\mathrm{MWh_{th}a^{-1}}$][b]	–465.3	–510.3	–49.7	–40.6
Percentage of heat deficit referred to total heat demand [%][c]	3.6	3.6	0.4	0.3
Sum of monthly surplus heat [$\mathrm{MWh_{th}a^{-1}}$][b]	+1152.9	+114.4	+163.3	+40.6
Percentage of surplus heat referred to total available heat from CHP unit [%][d]	8.7	0.9	1.2	0.3
Stored heat due to increased temperature at the end of the year [$\mathrm{MWh_{th}a^{-1}}$][e]	0.0	0.0	13.0	10.9
Annual heat-saving potential [$\mathrm{MWh_{th}a^{-1}}$][f]	1618.2	624.7	213.0	81.2
Stored heat [$\mathrm{MWh_{th}a^{-1}}$][g]	5592.4	6148.2	5886.6	5945.0
Stored heat based on total biogas [$\mathrm{kWh_{th}m_N^{-3}a^{-1}}$]	1.4	1.5	1.5	1.5
Stored heat based on digester volume [$\mathrm{kWh_{th}m_N^{-3}a^{-1}}$]	349.5	384.3	367.9	371.6
Degree of utilization [%][h]	47.7	48.0	47.9	47.9
Storage temperature [°C][i]	37.0	42.0	42.0	43.6

[a] Monthly average of digester temperature. [b] Annual sum for storage term from heat balances divided into heat deficit and surplus heat. [c] Percentage of additional heat needed to meet the demand. [d] Percentage of surplus heat exceeding the demand. [e] Stored heat equals the excessive heat stored due to difference of digester temperature in December and January of the same year. [f] Sum of annual amount of surplus heat and heat deficit based on storage term from heat balances. [g] Addition of monthly stored heat based on difference between digester and raw sludge temperature. [h] Defined here as ratio of stored heat (in comparison to raw sludge temperature) to added heat to digester (heat used for compensation of transmission and conversion, storage and conversion losses as well as heating up raw sludge). [i] Maximum digester temperature.

Regarding one year, storage of heat occurs when the digester temperature at the end of the considered year is higher than at the beginning in scenarios IIa and III. Thus, $13.0\,\mathrm{MWh_{th}a^{-1}}$ and $10.9\,\mathrm{MWh_{th}a^{-1}}$ are stored due to raised digester temperature. The phase of cooling down lasts into the following year as increased differences between raw sludge and digester temperature occur. However, the higher digester temperature in winter months causes heat deficits in the first months of the year whereby the digester temperature is self-regulated within the interaction between heat supply with the CHP unit and boiler as well as heat demand of the digester.

The performance as heat storages can be described by several parameters such as specific stored heat based on digester volume and total produced biogas, storage temperature as well as degree of utilization (Tab. 3). The specific stored heat based on produced biogas varies between 1.4 and $1.5\,\mathrm{kWh_{th}m_N^{-3}a^{-1}}$ and based on the digester volume between 349.5 and $384.3\,\mathrm{kWh_{th}m^{-3}a^{-1}}$. While the maximum storage temperature is equivalent to the maximum digester temperature, the ratio of available to added heat expressed as degree of utilization is around 48 % for all scenarios.

In the context of a holistic heat management, it is recommended to identify heat-saving potentials on basis of heat balances. While scenario III indicates the highest potential for heat-saving, the performance as heat storage of scenario II provides the best results which can be traced back to set the minimum of 37 °C in winter. Although, scenario II might not be the energetically best operation strategy for a holistic heat management at WRRFs regarding the annual amount of heat deficit and surplus heat. However, for evaluation of energetic assessment considering both heat-saving potential and amount of stored heat is essential. As the storage size represents an important aspect for designing conventional heat storage, the amount of stored heat based on the available digester volume seems to be most applicable for describing performances of digesters as heat storage.

3.3 Effects on Energy Flows and Emissions within the Heating System of Digesters

In contrast to heat balances on a daily and monthly basis, energy flows of sludge, biogas, heat, electricity, and losses are shown in more detail in energy flow diagrams for each scenario (Fig. 4). Energy flows of raw and digested sludge, total biogas, and electricity demand of digesters are equivalent for all scenarios. Here, conversion of biogas in the boiler with thermal efficiency of 95.0 % partly compensates the heat deficits. Usage of biogas for

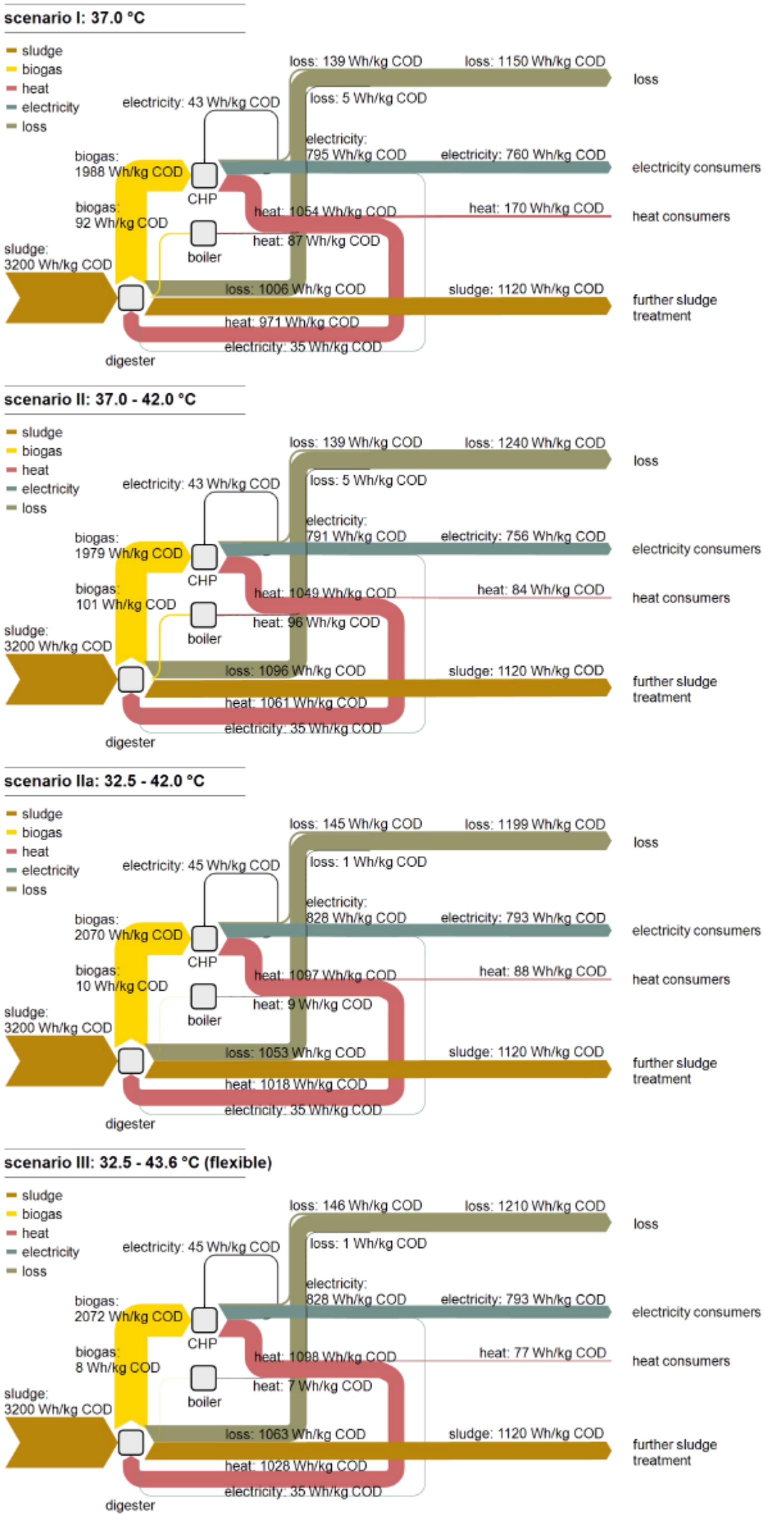

Figure 4. Energy flow diagrams around the heating system of digesters with focus on annual flows of (raw/digested) sludge, heat, electricity, and losses for each scenario based on results from heat balances. Reference value is the annual COD load of $12\,070\,\mathrm{Mg_{COD}a^{-1}}$ in raw sludge. Effluent "losses" summarize individual losses from operation of the digesters (heat and electricity demand of the digester and residual of sludge and biogas in relation to raw sludge), usage of biogas in the CHP unit and boiler. Effluent "heat" contains hot water demand, heat demand of operation buildings, and surplus heat.

additional heating in the boiler results in less available electricity for several electricity consumers. While 95.6 % of biogas is used in the CHP unit in scenario I, 95.2, 99.5, and 99.6 % of biogas is provided for heat and electricity conversion in the CHP unit in scenarios II, IIa, and III.

In each scenario, the main heat consumer is the digester itself due to heating up raw sludge as well as compensation of transmission and residual heat in sludge and biogas. Surplus heat can be used by further consumers whereby the heat demand of operation buildings and hot water is already $74\,\mathrm{Wh_{th}kg_{COD}}^{-1}$ in each scenario. The maximum available amount for heat consumers is around $170\,\mathrm{Wh_{th}kg_{COD}}^{-1}$ in scenario I (equals $2052.1\,\mathrm{MWh_{th}a}^{-1}$). With increasing flexibility of digester temperature and thus less surplus heat, the available heat for heat consumers decreases to a minimum of $77\,\mathrm{Wh_{th}kg_{COD}}^{-1}$ in scenario III (equals $939.8\,\mathrm{MWh_{th}a}^{-1}$).

Electricity consumption is considered for the digester (pumping of raw sludge feeding and heating of sludge in heat exchangers, mixing) and the self-consumption of the CHP unit. Available electricity for further consumers onsite is dependent on the extent of biogas usage in the boiler for compensation of heat deficits. In total, the available electricity for further consumers is quantified to $760\,\mathrm{Wh_{el}kg_{COD}}^{-1}$ for scenario I, $756\,\mathrm{Wh_{el}kg_{COD}}^{-1}$ for scenario II as well as $793\,\mathrm{Wh_{el}kg_{COD}}^{-1}$ for scenarios IIa and III (equals 9172.3, 9129.3, 9568.0, and $9576.7\,\mathrm{MWh_{el}a}^{-1}$). Thus, low usage of biogas in boilers (scenarios IIa and III) leads to a higher amount of available electricity.

As there are several electricity consumers, efforts for increasing the electricity supply with CHP units, as well as decreasing electricity consumption, are indeed of great importance at WRRFs. Further, electricity supply is linked to economic aspects considering purchase prices for electricity of around $18.25\,\mathrm{ct\,kWh_{el}}^{-1}$ for industrial purposes in Germany [30]. In total, ratios between electricity and heat for energy consumers are around 4.5, 9.0, 9.0, and 10.2 indicating more available electricity when the digester temperature is operated more flexible.

Total losses are summarized by individual losses due to operation of the digester as well as usage of biogas in the CHP unit and boiler. For all scenarios, losses of digesters are quantified to around 88 % of total output flows. The greatest part causes the sum of transmission as well as heat quantity of biogas and digested sludge leaving the digester usually unused.

Besides energetic aspects considered in heat balances and energy flow diagrams above, approaches for holistic heat management with compensation of heat deficits and management of surplus heat require assessment of ecological effects in form of equivalents of CO_2. In comparison to reference scenario I, there is a great potential of heat-saving with only slight changes of inner energy flows when the digester temperature is adapted to the seasons. Here, differences in usage of biogas in the CHP unit and boiler, efforts for managing surplus heat as well as available electricity for further consumers are taken into consideration.

In scenario I, around $737.8\,\mathrm{t_{CO2\text{-}eq}a}^{-1}$ is estimated as reference value. With increasing flexibility of the digester temperature, emissions decrease to 628.6, 350.1, and $328.3\,\mathrm{t_{CO2\text{-}eq}a}^{-1}$ for scenarios II, IIa, and III. Thus, the highest reduction can be assumed for scenario III by around 55.5 % in comparison to scenario I. Additionally, aspects such as biosolids quality and dewaterability depending on the digester temperature might also influence emissions of CO_2. However, here only CO_2-eq from energetic aspects are considered.

4 Conclusion

Using digesters as heat storage with variation in digester temperatures is an energetically holistic approach for modern heat management implemented at WRRFs. A flexible digester temperature enables a significant reduction of heat deficits and storage of surplus heat using an already existing storage volume of digesters onsite. Assessment of energetic aspects is based on heat balances and energy flow diagrams for four scenarios differing in flexibility and extent of digester temperatures.

The heat-saving potential of digesters constantly operating at 37 °C is enormous as usage of biogas in boilers usually compensates the heat deficits. Thus, surplus heat has to be converted with additional energetic expense in emergency coolers. Comparison of four scenarios showed that a flexible digester temperature can reduce heat deficits and surplus heat to a minimum and the performance of heat storage can be improved. Flexible digester temperatures between 32.5 and 43.6 °C show the best overall performance regarding minimization of heat deficits and surplus heat, performance as heat storage and saving of emissions, although digester temperatures between 37.0 and 42.0 °C show great performance as heat storage.

For flexible operation of digester temperatures, operators have to pay attention not to exceed recommended temperature changes to maintain the process stability for anaerobic degradation which is not the case in the considered scenarios. Further, the authors currently work on determination of relevant process parameters for operation of digesters between meso- and thermophilic temperatures.

The presented heat balances and energy flow diagrams are significantly influenced by chosen boundary conditions such as site-specific heat consumers, moderate climate and characteristic raw sludge, and air temperatures for Central Europe. However, the procedure can be adapted to different climate zones, further heat consumers, and relevant aspects for prospective water and sewage sludge treatment (such as sludge drying, deammonification, co-digestion, hygienization, cooling energy, access to heat networks) leading to quantitative changes in heat deficits and surplus heat and therefore can influence the energetic assessment of flexible digester temperatures.

Acknowledgment

The research work was funded by the Federal Ministry for Economic Affairs and Energy in Germany within the research project FLXsynErgy (Flexible and fully energetic usage of biogenic residues and waste material: digesters and biogas plants as energy consumer, storage and supplier) within the seventh energy research program in the field “Energetic use of biogenic residues and waste materials”. Open access funding enabled and organized by Projekt DEAL.

The authors have declared no conflict of interest.

Abbreviations

CHP	combined heat and power
COD	chemical oxygen demand
CO_2-eq	equivalents of CO_2
PE	population equivalent
TVS	total volatile solids
VS	volatile solids
WRRF	water resource recovery facility

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