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Summary

In Switzerland, there is considerable untapped potential for the energetic utilisation of manure (2.75 TWh/a). In the coming years, this is to be used to produce high-quality, renewable biogas, which can contribute to the decarbonisation of the Swiss energy system. Renewable gaseous fuels are an important part of the energy strategy, as they are used where electrification is difficult or very uneconomical. In contrast to the current situation, in which a large proportion of agricultural biogas plants convert the gas produced into electricity on-site, biogas plants are to feed directly into the gas grid more often in future, provided an adequate grid connection possibility. However, this requires alternative heating of the digesters, as the generously available waste heat from a combined heat and power (CHP) plant cannot be utilised as in the case of electricity generation.

Based on the case study of a planned biogas plant in Wittenbach, an energy concept for a gas-feeding biogas plant was developed, whereby an innovative combination of heat exchanger, heat recuperation, and a heat pump was investigated using numerical simulations. This concept significantly improves on the Swiss status quo, which consists of utilizing waste heat from a CHP. To this end, the relevant heat and mass flows of the biogas plant were modelled. Under the chosen conditions, the entire heating requirement of the digesters can be covered over the entire year by the heat exchanger, the heat recuperation from gas processing and the heat pump alone. The critical value of the minimum digestate storage temperature (5 °C) is not violated in this case, but is met with a margin of >2 °C.

In a sensitivity analysis, various aspects of the modelling and assumptions were examined more closely in order to quantify their influence on the results. For this purpose, selected parameters were varied within a certain range. It was found that in most cases there is a considerable margin with respect to a violation of the prescribed minimum digestate storage temperature. Problematic combinations were found mainly in the case of high heat exchanges between the slurry storage and the environment, and strongly increased heating requirements without a correspondingly higher mass flow. While the first problem (poorly insulated slurry storage) can be prevented by appropriate design, the second problem (e.g. very cold year, unexpected heat losses) is more difficult to solve, but also benefits from good insulation.

The simulations show that no additional heating system is needed for normal operation of the plant, except for redundancy considerations and for start-up. Figure 1 shows a summary of the relevant net biomethane and electricity production for year-round digester heating according to the energy concept presented in this study, compared to a conventional natural gas heating system as well as a combined heat and power (CHP) system.

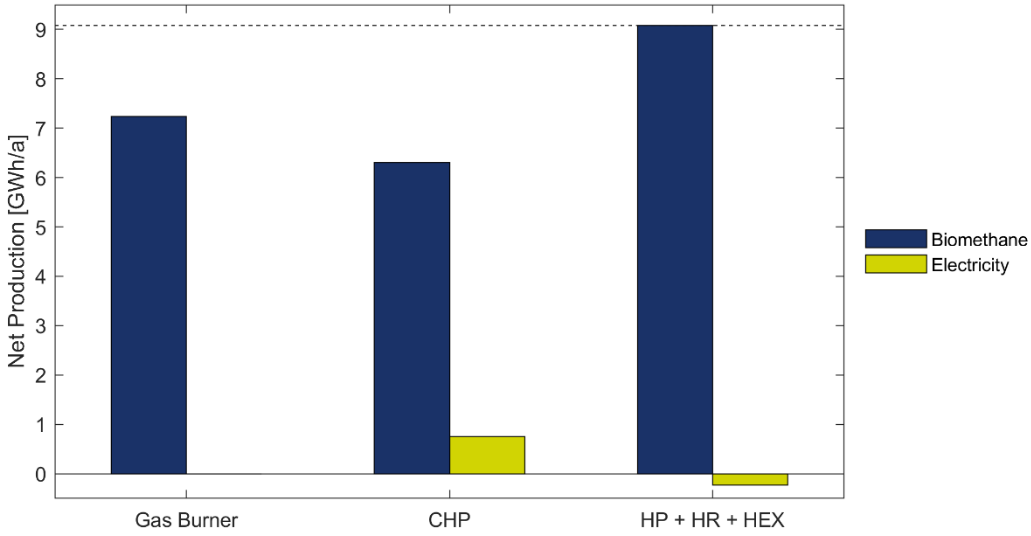

Figure 1. Comparison of annual net biomethane and electric power production of the planned biogas plant in Wittenbach, utilising different digester heating systems. Based on an annual biomethane production of 9.08 GWh, a gas burner (95% efficiency) utilises 1.80 GWh while a CHP self-consumes 2.78 GWh, while producing 0.75 GWh of electricity. In contrast, the combination of heat pump, active heat recovery in the gas compression unit as well as utilizing a substrate/digestate heat exchange does not self-consume biomethane, but requires an electrical input of 0.23 GWh/a.

1 Introduction

1.1 Context

According to the VSG annual statistics of 2023, natural gas consumption in Switzerland totalled 33’408 GWh in 2022, of which only 470 GWh was covered by locally produced biomethane. A total of 42 plants are currently in operation in Switzerland, feeding biomethane into the gas grid. In addition, a total of 2’306 GWh of biomethane is imported, for which certificates have been acquired. Renewable gases covered a share of 8% of Switzerland's total gas consumption in 2022, although this share is clearly increasing from a low level (2020: 4.2 %) (VSG Jahresstatistik 2023, 2023).

The greatest additional potential for biomethane production in Switzerland presents the category of farmyard manure from agriculture, having a potential of 9.9 PJ/a (2.75 TWh/a) of methane production from 26.9 PJ of available primary energy (Thees et al., 2017). According to the Zero Basis scenario of the Energy Perspectives 2050+, the share of biomethane in Swiss gas consumption should rise to 100% in the long term, albeit with the inclusion of considerable imports (SFOE, 2021b). The scenario outlines a biomethane consumption of 15.33 TWh/a, with 11.75 TWh/a being imported. Switzerland's total sustainable biomethane potential is therefore utilised to its full extent (SFOE, 2021a).

Biomethane produced in a biogas plant (BGP) can be fed into the gas grid or converted into electricity on site in a combined heat and power plant (CHP), with heat being generated as a by-product. The majority of agricultural biogas plants installed in Switzerland operate according to the second principle. In 2022, biogas with a calorific value of 551 GWh was produced in agricultural CHP plants, of which only 11.08 GWh (approx. 2%) was fed into the gas grid (SFOE, 2023). The heat produced in the CHP plant is primarily used to heat the digester and is sold profitably as a secondary priority (e.g. via a heat network or for contract drying). In 2022, a total of 151.4 GWh of heat was used for digester heating, while 60.5 GWh of heat was used elsewhere (SFOE, 2023). While agricultural BGP are only subject to the restriction that the heat requirement of the energy plant must be covered by heat utilisation from the CHP plant or other renewable sources, other BGP must utilise at least 40% of gross heat production for other purposes (SR 730.03, 2023).

Biogas digesters should be operated at an as constant a temperature as possible, whereby the optimum temperature level for maximising the gas yield is depending on various factors. Agricultural BGPs are usually operated in a mesophilic range at temperatures between 37 °C and 42 °C, although higher operating temperatures should be aimed for depending on the substrate composition (Leitfaden Biogas, 2016). Depending on the composition of the initial substrate, the fermentation process consists of a mixture of endothermic (e.g. saturated fatty acids and proteins) and exothermic (e.g. carbohydrates) reactions (Zhang et al., 2014). Overall, the reactions are usually slightly exothermic, but do not supply heat to the extent required to heat the substrate and compensate for the continuous transmission losses. The digesters must therefore be actively heated to ensure a constant temperature level.

There are two common approaches to providing this heat, depending on the utilisation method: In a power-generating BGP, the waste heat from the CHP can easily cover the heat requirements of the digesters, while in a gas-feeding BGP, part of the produced biogas can be burnt for own consumption. Depending on the thermal insulation of the digester, among other things, up to 30% of the biogas produced must be used for this (Avila-Lopez et al., 2023), which worsens the energy efficiency and gas yield as well as the financial performance and carbon footprint.

Compared to the current Swiss state-of-the-art, there are a number of other measures that can be implemented. As part of the SWEET-EDGE project, an energy variant study was carried out to analyse the potential, interaction and challenges of these measures. The following measures were considered:

- Heat recovery via substrate/digestate heat exchanger.
- Heat extraction in the gas compression before the biomethane feed-in.
- Use of a heat pump with the digestate storage and/or secondary digester as a heat reservoir.

Another possible tappable heat source would be a CO_2 liquefaction plant, which will probably often be part of a biogas plant in the future. However, this was not considered further in this study. Digester heating via wood pyrolysis (with combined production of biochar) was initially considered in detail as part of this study, but does not represent a sensible solution, mainly due to the incompatible operating optima. The heat demand of a biogas digester fluctuates both seasonally as well as with the temperature in general. Further, changes in substrate feeding rates and substrate composition can influence this heating demand. On the other hand, pyrolysis ovens capable of producing EBC-certified biochar (a necessary prerequisite for viable commerical operation) need to be operated at close to optimal conditions, with deviations generally lowering the quality of biochar produced significantly. After conducting a market study on available pyrolysis plants and their specifications, a wide variety of combinations and cascades were studied in detail. Although there certainly are cascades that are able to meet the heat demand at all times (without strongly violating their own operational requirements) they consist of multiple different types of pyrolysis plants, thus introducing a lot of complexity. Ultimately, the revelation that current biogas plants do not make use of easily achievable recuperation and efficiency measures voided the need for close examination, as the remaining heat demand (after implementation of said measures) is decidedly below the output level of commercially available pyrolysis plants - and characterized by stronger relative fluctuations, clashing even more with the aforementioned operational requirements.

The proposed measures of heat exchanger, heat extraction in the gas compression, and use of a heat pump do not represent technical innovations in themselves. For example, shell-and-tube heat exchangers for biogas plants are already being produced in series, but have not yet been used in Switzerland, or only very occasionally. The need for a reduction in the required process heat or its provision in the first place only arises with the elimination of the CHP plant through direct feed-in of the biogas, which is currently very rare, but is expected to play a greater role in the future Swiss energy system (SFOE, 2021b). Biomethane is a very high-quality energy carrier which, thanks to its high energy density and good storability, can make an important contribution to making renewable generation more flexible, including for supplying regional high-temperature processes. Direct on-site electricity generation forfeits a large part of these advantages.

The challenge consists of covering the seasonally fluctuating heat demand as efficiently as possible with locally available heat sources. Using the case study of a planned biogas plant in Wittenbach (SG), the pertinent energy and mass flows are simulated over a model year.

1.2 Biogas plant Wittenbach

A biogas plant is to be built in Wittenbach (SG) that will feed biomethane directly into the natural gas grid (Keel & Scheibler, 2022). This utilisation method was chosen because, on the one hand, there is relatively easy access to the gas grid (grid access point located directly adjacent to the project site) and, on the other hand, there are no large potential heat consumers in the vicinity. In addition, the gas feed-in is very valuable from the perspective of the overall energy system. The project is being supported by SWEET-EDGE. The BGP with a combined digester volume of 4’712 m^3 will be fed mainly from a mixture of farmyard manure and acid whey from local suppliers and will be operated at a constant temperature of 45 °C. Due to the proportion of non-agricultural co-substrates (between 20 and 50 %), the planned plant is classified as a type C agricultural biogas plant (FOEN, 2021), producing recycling fertiliser. A raw gas production of 1.58 million m^3/a is targeted, with commissioning expected in 2025. Table 1 summarises the key energy figures for the plant.

Table 1. Key energy figures for the planned biogas plant in Wittenbach.

Parameter	Value	Unit
Raw gas yield	1'582'000	m^3/a
Biomethane yield	911'000	m^3/a
Average power	1'098	kW
Annual energy yield	9'082	MWh
Heating requirement	1'748	MWh

The biogas plant is being planned by the companies Laveba Cooperative, Energiewenden, NQ Anlagentechnik, Kuster + Hager Architekturbüro AG and the building administration of the municipality of Wittenbach. It is to be operated by a newly founded company with the participation of the Laveba Cooperative, the municipality of Wittenbach, as well as other business-related stakeholders. Figure 1 shows the overall scheme of the planned biogas plant with all peripheral components.

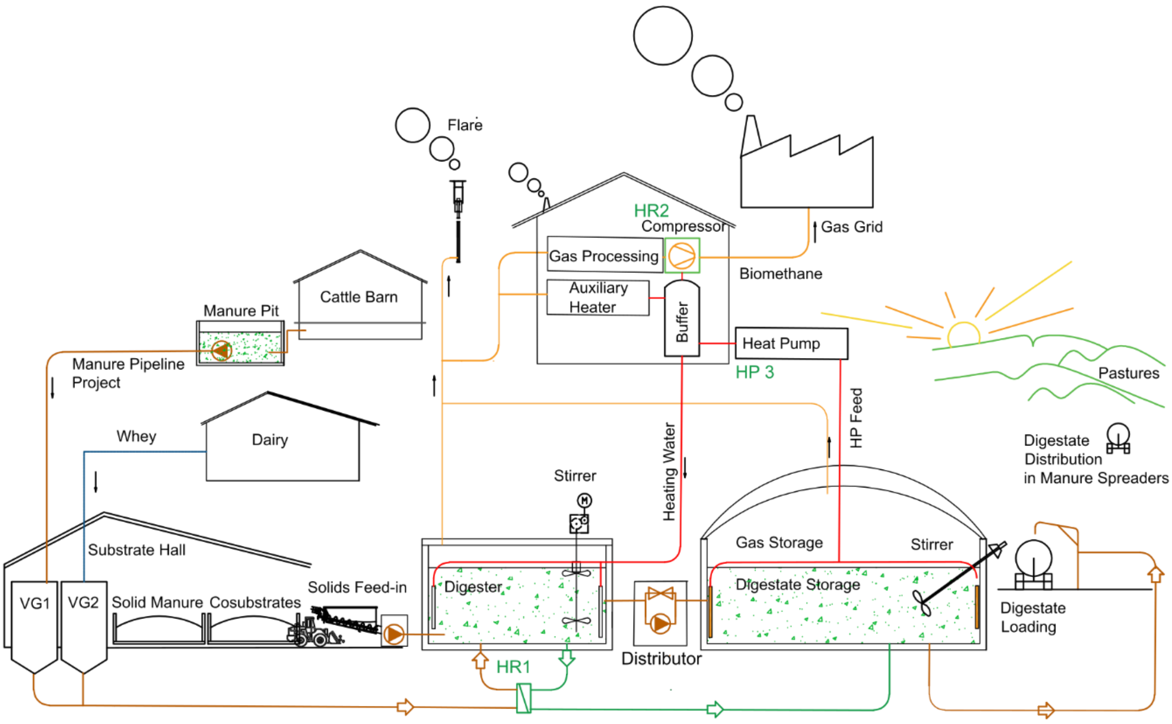

Figure 1. Overall diagram of the planned biogas plant in Wittenbach. The digester and digestate storage are combined here as one tank each. (Drawing: Mátyás Scheibler, EnergieWenden).

1.3 Heat sources

The digesters of the biogas plant can be heated by a combination of different heating systems. The systems considered are briefly presented below.

1.3.1 Substrate - digestate heat exchanger

A considerable proportion of the process heat required by the digester is used to heat the fresh substrate to the digester temperature. At the same time, the digestate exits the digester at a temperature of 45 °C. If secondary fermentation is omitted, the heat contained in the digestate can be introduced into the fresh substrate via a heat exchanger. Heat exchanger efficiencies of >60% can be achieved. Available heat exchangers are designed as tube-in-tube, spiral and double helix heat exchangers (Ökostrom Schweiz, 2015).

1.3.2 Heat extraction gas treatment

The Wittenbach biogas plant is expected to use a gas treatment system with a membrane separation process to separate the CO_2. This involves compressing the raw gas to a pressure of 5-16 bar and passing it through a membrane. The waste heat generated during compression can be used to heat the digester. Based on manufacturer information, two variants with an available waste heat of 12 or 24 kW_{th} are considered. The conservative variant with 12 kW_{th} is used for standard calculations.

1.3.3 Heat pump with digestate storage as a heat reservoir

The digestate produced is stored in a digestate storage mostly in winter, as it must not be spread on the fields outside of the growing season. Even after a significant amount of heat has been extracted by the heat exchanger, it is still a highly accessible heat reservoir. This can be utilised using a system of cooling loops in the digestate store. The digestate is cooled to a minimum temperature of 5 °C, which ensures its flowability. A comparable project was carried out in Germany for a pig fattening barn (Pommer, 2019). A potential reduction in CH_4 emissions was not part of this analysis, however a reduction of these emissions with the digestate temperature can at least be assumed (Baldé et al., 2016).

1.3.4 Additional heating system

In addition to the heat sources already described, a generic heating system is assumed, which acts as a fallback level and is also required for the initial start-up of the digester. However, the technology (e.g. wood chip burner, gas boiler) is unspecified; for the analysis, it is assumed that the heating system can cover any possible heat demand instantaneously. The specific heating system is then selected a posteriori on the basis of the calculated heating requirements.

2 Methodology

2.1 Modelling

The planned plant is set up as a point-modelled heat and mass transfer model. The tanks (digester and digestate storage) are each considered as homogeneous, perfectly mixed entities. Figure 2 shows a simplified process flow diagram of the plant. The individual digesters and digestate storage tanks are each summarised as a single tank. The discretised model equations were implemented in MATLAB.

The initial substrate consists of a solid and liquid fraction (see also Figure 1). While the solids are fed directly into the digester, the liquid fraction is passed through a heat exchanger, and from there into the digester. The digestate passes through a screw-press separator, which returns the solids to the digester. The liquid parts are passed through the heat exchanger, and from there into the digestate storage. For space reasons, the digestate storage in Wittenbach is smaller than the total amount of digestate produced in winter. The digestate is always removed from the digestate storage, even if the digestate is transported to these external slurry storage facilities if local capacity is insufficient. This means that the residual heat contained in the digestate can still be utilised.

The heating cascade of the digester ultimately consists of passive heat recovery using a substrate/digestate heat exchanger, waste heat from gas treatment/compression, active heating using the heat pump and additional auxillary heating, which should not be required under normal circumstances.

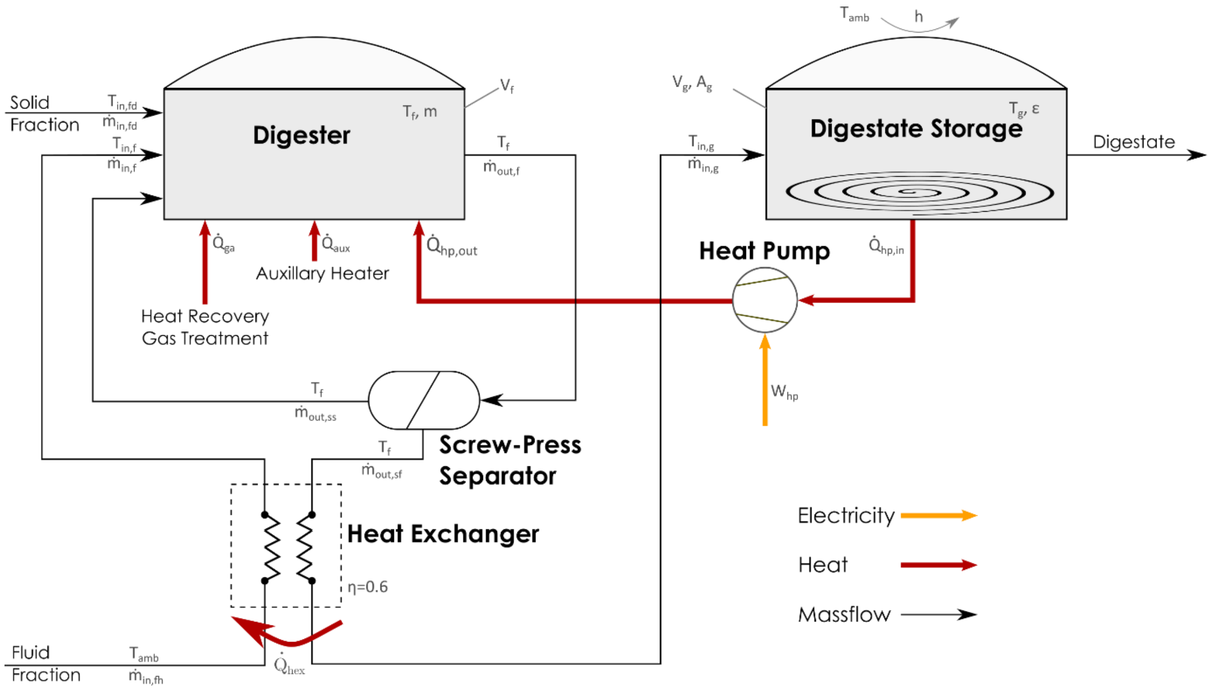

Figure 2. Simplified process flow diagram of the planned biogas plant with digester and digestate storage with all pertinent variables indicated. The liquid fraction of the initial substrate is first passed through a heat exchanger and then enters the digester. The solid parts are fed directly into the digester. After the retention time, the digestate flows out of the digester into the separator, whereby the liquid parts enter the heat exchanger, and from there into the digestate storage. After additional biological and mechanical measures, the solid parts are returned to the digester, where they decompose further. The digester heating system consists of a heat pump, which extracts heat from the digestate storage, waste heat from gas purification, and an auxiliary heating system, which is not required during normal operation.

The following assumptions are made to simplify the model:

- The filling level of the digester is constant, so the mass flow into and out of the digester is identical.
- All material properties are constant in temperature and time.
- The digester temperature is constant at $T = 45\ °C$.
- The inlet temperature of the fresh substrate is identical to the outside temperature.
- When calculating the heat transfer from the digestate storage to the environment, an average linear heat transfer coefficient over the entire surface (heat transfer from the wall to the air and from the floor to the ground) is assumed in a very simplified manner, whereby the heat transfer is calculated as a function of the outside temperature (air).
- The properties of the substrate are homogeneous and the containers are perfectly mixed.
- The digesters and the digestate storage are each assumed to be one tank, even if in reality they consist of several individual tanks. This fact was taken into account in the calculation via the surfaces and volumes.
- The digestate is considered inert after leaving the digester, i.e. there is no heat input or output due to biological reactions.

2.2 Model equations

2.2.1 Boundary conditions

The mass flow into the digester is modelled using a 1-year sinusoidal curve, which reduces the substrate input in summer compared to the substrate input in winter by a specifiable factor F, such that

$$\max(\dot{m})\,(1-F) = \min\,(\dot{m}) \quad (1)$$

with the maximum occurring on January 1st and the minimum on July 1st. The corresponding equation is

$$\dot{m}_{IN,F}(t) = \dot{m}_{avg} \cdot \left(1 + \frac{F}{2-F} \cdot \left(\frac{2\pi t}{8760}\right)\right) \quad (2)$$

where $\dot{m}_{avg}$ is the annual average value of the substrate input, and $\dot{m}(t)$ is calculated in units of kg/h. Figure 3 shows the modelled substrate input over the entire year. The summerly reduction in substrate input is due to the partially grazing herds. In the case shown here, a reduction of 10% in summer compared to winter is calculated on the basis of empirical values (T.Keel, personal communication, 2023).

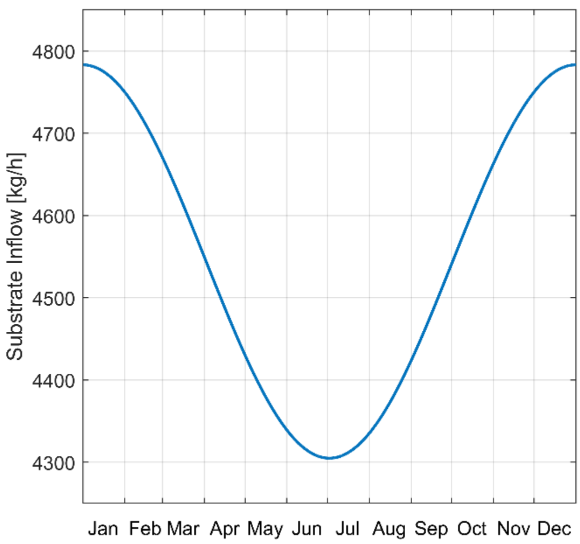

Figure 3. Substrate input over the entire model year with an annual input of 39'806 tonnes, average input of 4'544 kg/h, maximum input of 4'782 kg/h and minimum input of 4'305 kg/ h . This corresponds to a reduction of 10% in July compared to January.

The removal of digestate from the storage facility is modelled discretely. In principle, digestate is removed over the summer until the storage is empty at the end of September. During the vegetation rest period, no digestate is spread on the fields. This only happens again after the start of the growing season. This date can change depending on the weather and also depends on the crops to be fertilised (Flisch et al., 2009). It is assumed that digestate removal begins at the beginning of April and is constant throughout the summer. However, as the filling level is only significantly relevant in winter within the context of this study, this should have no influence on the results. With a total quantity of 39'806 tonnes over the entire year, a withdrawal of 9'214 kg/h during April to September is therefore expected, and no withdrawal in winter. Figure 4 shows the modelled digestate removal over the entire year.

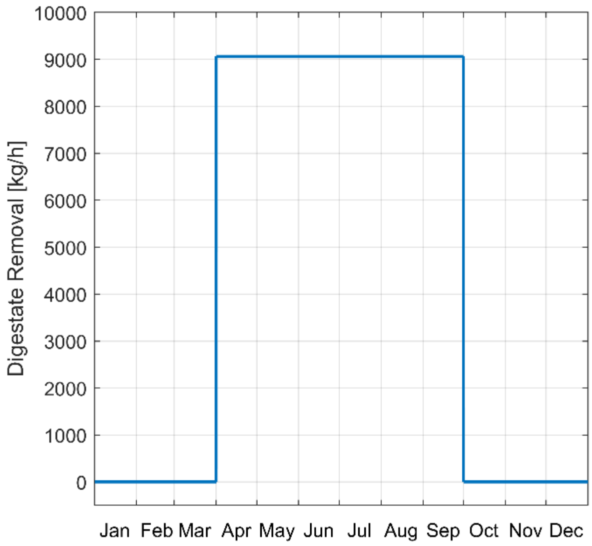

Figure 4. Digestate removal over the entire model year with a total removal of 39’806 tonnes. No digestate removal from October to March. Digestate removal is modelled as constant over the summer.

The outside temperature was determined on the basis of historical weather data in St. Gallen. Specifically, temperatures from 2021 were used. In comparison to long-term average temperatures, variations on short time scales are also taken into account. The air temperature 2 m above ground was used. The heat requirement of the digester was modelled as follows

$$Q_F = 262.4\,kW - 6.18\,\frac{kW}{K} \cdot T \tag{3}$$

where Q_F is in kW_{th} and T (outside temperature) in °C. This function is created by regressing the monthly heat demand estimated by the plant manufacturer with the historical outside temperatures. To simplify matters, it is assumed here that the heat demand of the digester is a linear function of the outside temperature. The consideration of fluctuations in the heat demand with a higher temporal resolution is a central component of this analysis. The heat requirement Q_F includes the heating of the substrate as well as the equalisation of transmission losses. Heat introduced by the biological reactions is also already taken into account here (as a negative heat demand). Figure 5 shows the heat demand over the entire model year.

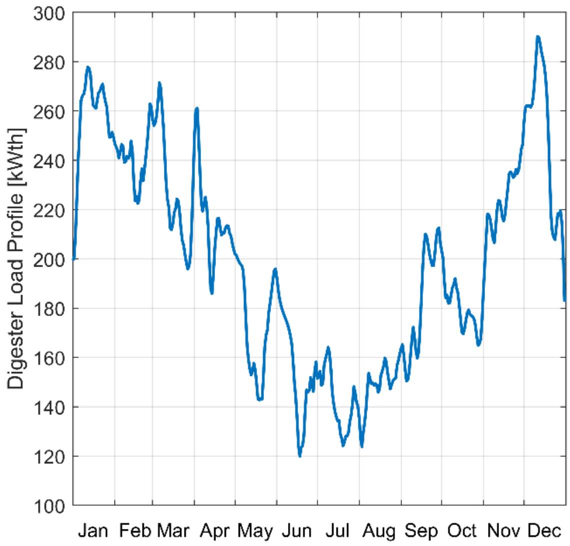

Figure 5. Modelled heat demand of the digester based on historical weather data. The total annual demand is 1'748 MWh_{th} (note that the Y-axis does not start at 0).

2.2.2 Mass flows and fill levels

The substrate input is divided into a solid and a liquid fraction, whereby the solid fraction ($\dot{m}_{in,fd}$) is fed directly into the digester, while the liquid fraction ($\dot{m}_{in,fh}$) first passes through the heat exchanger. The fractions are defined as follows:

$$\dot{m}_{in,fd} = \alpha_F \cdot \dot{m}_{IN,F}, \quad \dot{m}_{in,fh} = (1 - \alpha_F) \cdot \dot{m}_{IN,F} \tag{4}$$

α_F denotes the mass fraction of the solids flow. The mass balance of the digester is therefore:

$$\dot{m}_{IN,F,TOT} = \dot{m}_{in,fd} + \dot{m}_{in,fh} + \dot{m}_{out,ss} \tag{5}$$

The press screw separator divides the digestate discharged from the digester ($\dot{m}_{out,f}$) into a solid ($\dot{m}_{out,ss}$) and a liquid ($\dot{m}_{out,sf}$) portion. This also takes place according to fixed proportions:

$$\dot{m}_{out,ss} = \alpha_S \cdot \dot{m}_{out,f}, \quad \dot{m}_{out,sf} = (1 - \alpha_S) \cdot \dot{m}_{out,f} \tag{6}$$

As described in the assumptions, the filling level of the digester is constant, i.e. consequently also $\dot{m}_{out,sf} = \dot{m}_{IN,F}$ at constant density. Here, the simplification is made that the biogas being taken from the fresh substrate is neglected. In percentage terms, approx. 2 % of the incoming mass is discharged via the biogas, which is why this simplification is justifiable (Bowman et al., 2022). Together with (6), the mass flow from the digester can be calculated:

$$\dot{m}_{out,f} = \frac{\dot{m}_{IN,F}}{(1 - \alpha_S)} \tag{7}$$

Accordingly, an increase in the recirculation of unfermented material (α_S) at a constant external substrate input ($\dot{m}_{IN,F}$) increases the absolute flow rate through the digester. On the other hand, for a given digester throughput, the absolute required external substrate input decreases with increasing recirculation. The recirculation mass flow is as follows

$$\dot{m}_{out,ss} = \frac{\alpha_S}{(1-\alpha_S)}\, \dot{m}_{IN,F} \tag{8}$$

It is important to emphasise that the recirculation of the solid fraction from the press screw separator does not add or remove any additional mass from the system (the same applies to the energy side if no losses are assumed). Furthermore, there are no mass inflows and outflows between the digester and digestate storage , therefore $\dot{m}_{IN,G} = \dot{m}_{out,sf} = \dot{m}_{IN,F}$.

Figure 6 shows the net inflow into the digestate storage facility over the entire year. Figure 7 shows the filling level curve (in m^3) over the entire year, together with the assumed volumes of the slurry storage facility (3 separate tanks). For the further calculations, it is assumed that the slurry storage facility is limited to 11'000 m^3 and that any additional capacity required is rented externally. Operationally, the fermentation residue from the digester is always fed into the digestate storage first. When this is full, the same amount of digestate is simultaneously removed from the store and transferred to an external store.

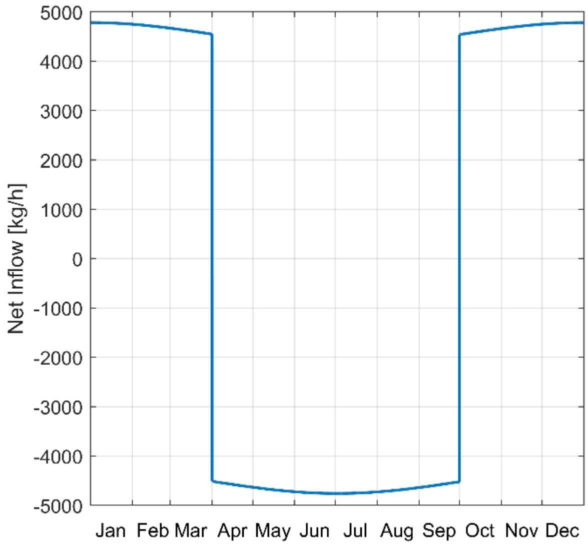

Figure 6. Net inflow into the digestate storage over the entire model year. Positive values correspond to an inflow into the digestate storage, negative values to an outflow.

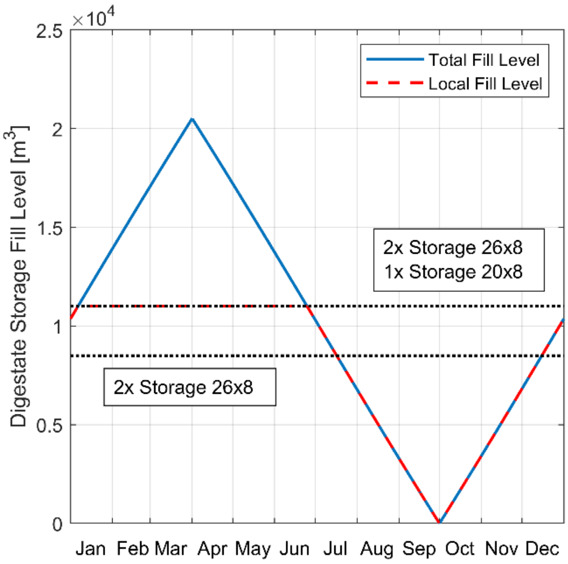

Figure 7. Modelled fill level of the digestate storage tank, in m^3. The dotted lines show the volumes of the digestate store - this figure may vary depending on the configuration of the post-digester/fermentation store. The red line shows the local fill level (limited by storage capacity), the blue line shows the total fill level, which is made up of local and external capacity.

The filling level of the digester is constant, as described in the assumptions. However, the filling level of the digestate storage fluctuates during the year, which has a direct effect on the heat reservoir available to the heat pump and thus also on the associated temperature change. The fill level of the digestate storage is calculated as follows:

$$\varepsilon(t) = \min\left(1, \varepsilon_0 + \frac{1}{V_G \cdot \rho} \int_0^t (\dot{m}_{IN,G} - \dot{m}_{OUT,G})\, dt\right) \tag{9}$$

where ε denotes the fill level of the digestate storage tank (0: empty, 1: full), ε_0 the initial state of the simulation (January 1st), ρ the density of the digestate and V_G the total volume of the locally available digestate storage. Equation (9) corresponds to the red dashed line in Figure 7.

2.2.3 Heat flows

The heat flow $\dot{Q}_{HEX}$ is determined by the temperatures of the fresh substrate and the digester, the efficiency of the heat exchanger and the direct feeding of the digester. The direct feeding of part of the incoming substrate means that the mass flows in the heat exchanger are not symmetrical, which results in a somewhat more complicated derivation. The heat flow can be defined on both sides:

$$\dot{Q}_{HEX} = \dot{m}_{in,fh} \cdot c_p \cdot (T_{in,f} - T_{amb}) \tag{10}$$

$$\dot{Q}_{HEX} = \dot{m}_{out,sf} \cdot c_p \cdot (T_f - T_{in,g}) \tag{11}$$

With constant material properties, these can be combined as follows:

$$\dot{m}_{in,fh} \cdot (T_{in,f} - T_{amb}) = \dot{m}_{out,sf} \cdot (T_f - T_{in,g}) \tag{12}$$

Since $\dot{m}_{in,fh} < \dot{m}_{out,sf}$ (and $c_p = \not{c}$), the efficiency of the heat exchanger can be formulated as follows:

$$\eta_{HEX} = \frac{T_{in,f} - T_{amb}}{T_f - T_{amb}} \tag{13}$$

This allows the temperature of the liquid fraction of the fresh substrate to be calculated:

$$T_{in,f} = T_{amb} + \eta_{HEX} \cdot (T_f - T_{amb}) \tag{14}$$

The combination of (12) and (14) results in the inlet temperature of the digestate storage tank,

$$T_{in,g} = T_f - \frac{\dot{m}_{in,fh}}{\dot{m}_{out,sf}} \left(\eta_{HEX} \left(T_f - T_{amb} \right) \right) \tag{15}$$

while the heat flow $\dot{Q}_{HEX}$ can be determined via equations (10) or (11):

$$\dot{Q}_{HEX} = \dot{m}_{in,fh} \cdot c_p \cdot \eta_{HEX} \cdot \left(T_f - T_{amb} \right) \tag{16}$$

The heat flows with reference to the heat pump initially follow the following equation:

$$\dot{Q}_{HP,OUT} = \dot{Q}_{HP,IN} + \dot{W}_{HP} \tag{17}$$

In addition, the definition of the COP (coefficient of performance) is used:

$$COP = \frac{\dot{Q}_{HP,OUT}}{\dot{W}_{HP}} \tag{18}$$

From equations (17) and (18) the heat extracted from the digestate store is a function of the heat supplied to the digester:

$$\dot{Q}_{HP,IN} = \dot{Q}_{HP,OUT} \cdot \left(1 - \frac{1}{COP} \right) \tag{19}$$

The COP is assumed to be constant. The heat flow from the auxiliary heating is referred to as $\dot{Q}_{aux}$. The heat recovery from the gas treatment system $\dot{Q}_{ga}$ is assumed to have a constant output of either 12 or 24 kW_{th} (see section 1.3.2).

2.2.4 Equations of state

The floor slab is considered as thermally active and is counted as part of the integral heat capacity of the digestate storage. With a thickness of d = 0.2 m, the volume of the floor slab is around 275 m^3. The heat capacity of concrete is approx. 880 J/(kgK), the density is 2'400 kg/m^3 . The thermal mass of the floor slab is referred to below as $(V\rho c_p)_{BP}$. It should be specifically noted that the thermal mass of the floor slab corresponds to only approx. 1.5 % of the thermal mass of the digestate storage tank when full, but contributes significantly to the numerical stability of the simulation when empty.

The energy balance of the digestate store can be formulated as follows:

$$\frac{\partial}{\partial t}\left(\left(\left(V\rho c_p\right)_{BP} + \varepsilon V\rho c_p\right)T_G\right) = \dot{m}_{IN,G}T_{IN,G}c_p - \dot{m}_{OUT,G}T_G c_p + hA(T_{amb} - T_G) - \dot{Q}_{HP} \qquad (20)$$

In words, equation (20) describes the following: The change in the internal energy of the digestate storage and the base plate is determined by the enthalpy flowing in from the digester (via the heat exchanger), the enthalpy flowing out through slurry extraction, the heat exchange with the environment and the heat extracted by the heat pump.

2.3 Program logic

Based on a known heat demand (see Figure 5), the digester is heated using a combination of the heat sources presented. These heaters are cascaded according to a program logic: the specified heat requirement of the digester is fed in part by the heat exchanger. The remaining heat requirement is then fed primarily by the heat recovery from the gas treatment system and secondarily by the heat pump, provided that the digestate temperature is above the specified minimum. The remaining heat requirement must be provided by an additional heating system.

The heat pump is controlled using simple logic: at any point in time, the maximum possible power the heat pump could extract from the digestate storage during a time step without violating the lower temperature limit is calculated. If this value is higher than the currently required heat output, the entire heat output is provided by the heat pump. If there is not enough heat available in the reservoir, the heat pump utilises the maximum possible, while the remaining part is provided by the additional heating.

2.4 Standard parameters

For the simulations, standard values were assumed for the parameters listed in Table 2. Simulations with deviating values were carried out specifically for the efficiency of the heat exchanger, the COP of the heat pump, and the heat transfer coefficient digestate storage - environment in order to check the sensitivity. However, the standard values generally represent relatively conservative assumptions.

Table 2. Standard values for simulations. Outdoor temperatures are based on historical weather data from 2021.

Name	Symbol	Value	Unit
Minimum temperature digestate storage	$T_{G,MIN}$	5	°C
Heat exchanger efficiency	η_{HEX}	0.6	-
COP heat pump	COP	3.5	-
Heat transfer coefficient digestate storage - surroundings	h	1	$W/(m^2K)$
Solids fraction fresh substrate	α_F	0.3	-
Solids recirculation	α_S	0.15	

The heat transfer coefficient digestate storage - environment was selected such that the convective heat loss in winter averages approx. 30 kW_{th}, which naturally depends on the temperature of the digestate storage. These values (scaled to the tank surface) are in the same order of magnitude as described in literature (Avila-Lopez et al., 2023; Hreiz et al., 2017), but the comparability is probably relatively complex. Figure 8 shows the modelled convective heat loss of the digestate storage tank (air & soil combined) over the entire year.

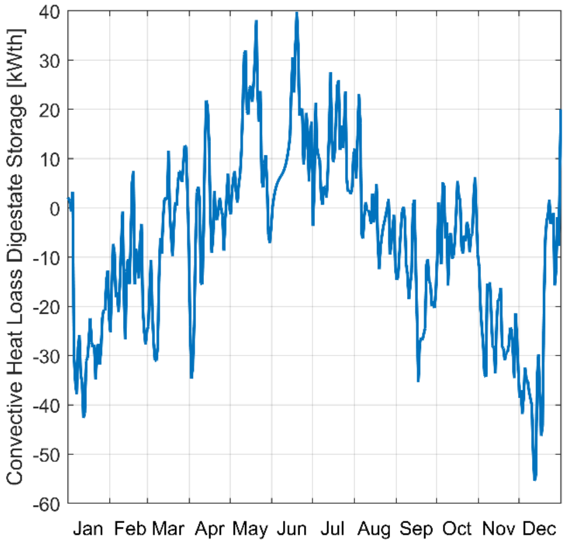

Figure 8. Modelled convective heat loss (air + soil) of the digestate storage over the entire year (temperatures from 2021), with standard values according to Table 2. Positive values correspond to heat transport *into* the digestate storage.

3 Results

As described in section 2.3 the program logic follows the sequence of first covering the heat requirement via a heat exchanger and recovery from the gas treatment system, then via a heat pump and finally by means of an additional heating system. As the steps are only interdependent in this direction, the results are also presented in this order.

3.1 Heat exchanger & recovery gas treatment

The residual heat requirement for the digester with a heat exchanger efficiency of 60 % and a recuperation capacity of the gas compression in gas treatment of 12 kW_{th} is shown in Figure 9. It should be noted that the assumptions of both the heat exchanger efficiency and the heat output of recuperation from gas treatment are rather conservative.

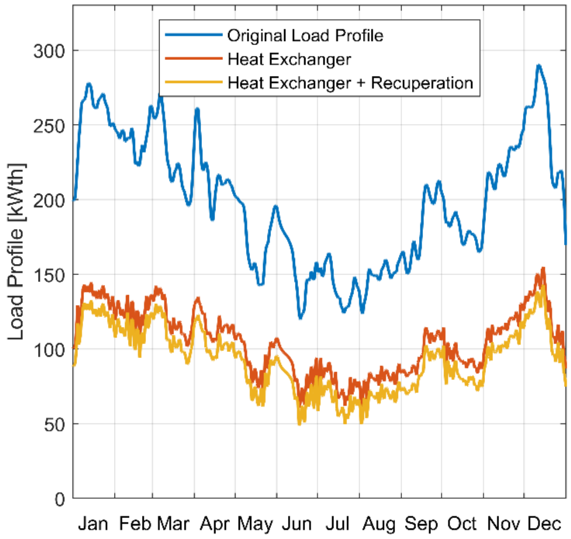

Figure 9. Heat demand of the digester over the entire year. The blue curve shows the original load profile, i.e. the total heat requirement of the digester. The red curve shows the remaining heat requirement after installation of the heat exchanger, the yellow curve shows the remaining heat requirement after additional utilisation of the waste heat from gas processing. This corresponds to the required output that the heat pump must provide.

3.2 Heat pump & digestate storage temperature

Based on the "reduced" load profile shown in Figure 9 (heat recovery via heat exchanger plus recovery of gas compression in gas treatment), a heat pump with $COP = 3.5$ is used to supply the residual heat if the temperature level of the digestate store permits this. Figure 10 shows the evolution of the inlet temperature of the digestate storage $T_{in,g}$.

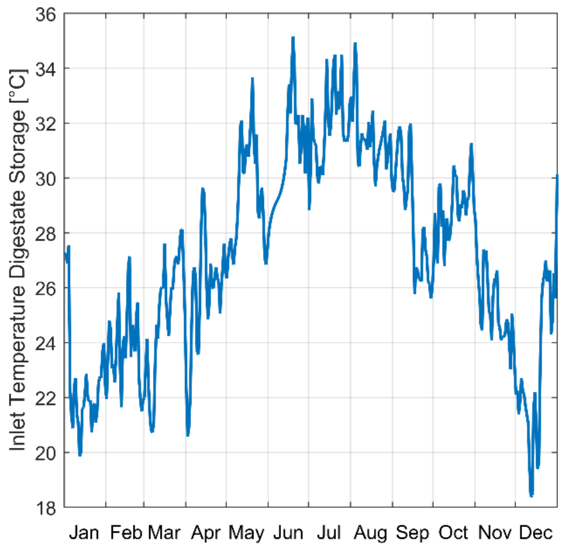

Figure 10. Inlet temperature of the digestate storage (°C) over the entire year. This corresponds to the outlet temperature of the digestate side of the heat exchanger, as there is no pipe heat loss between these points.

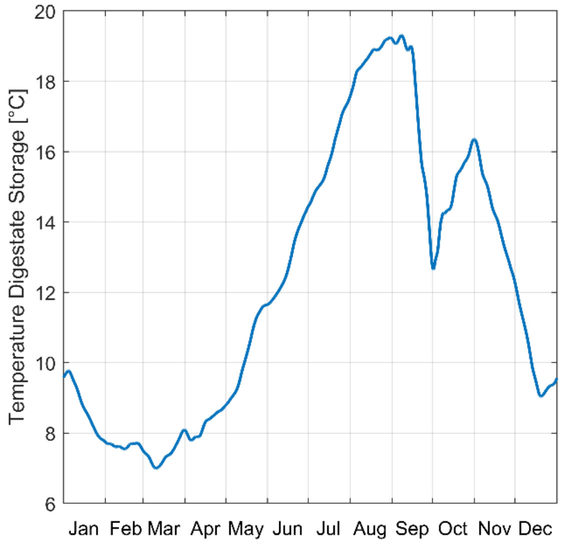

Figure 11. Temperature curve of the digestate storage over the entire year with heat extraction by the heat pump. During the period from the turn of the year to the beginning of July, the storage is full and there are no net inflows or outflows. The storage is empty at the end of September and is then refilled.

Figure 11 shows the temperature profile of the digestate storage over the entire year. The fill level of the local storage facility is shown in Figure 7 (red). In the first half of the year, there are no net mass inflows or outflows from the storage, as it is full. The storage is empty at the end of September and is then filled again. The temperature of the digestate storage does not fall below the critical level of 5 °C at any time, such that the heat pump can also operate constantly. The initial temperature is determined iteratively such that the same temperature prevails in the digestate storage at the beginning and end of the year. This prevents a poorly selected initial value from falsifying the results. The thermal output of the heat pump over the entire year is shown in Figure 12.

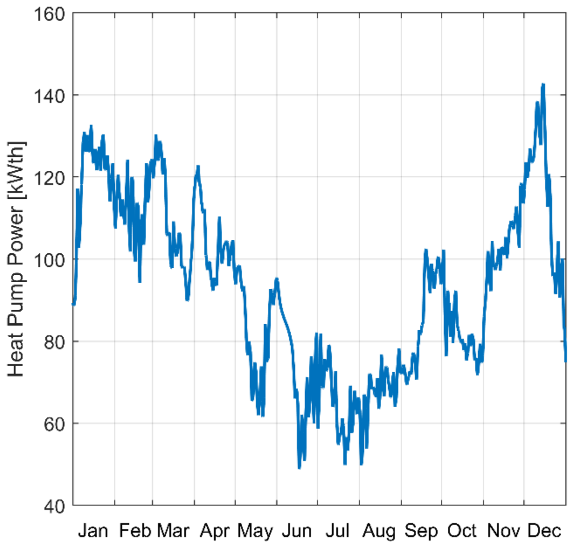

Figure 12. Thermal output of the heat pump over the entire year. The heat pump is not limited at any time by the temperature limit of the digestate storage tank.

Over the entire year, the heating requirement of 1748 MWh/a is covered by 826.4 MWh (47.3 %) heat exchanger, 105.1 MWh (6 %) heat recovery gas compression in gas treatment, and 814.8 MWh (46.6 %)

heat pump, which, with a COP of 3.5, therefore has an annual electricity consumption of 232.8 MWh. Figure 13 illustrates the proportions graphically. A heat pump with a maximum output of 150 kW_{th} achieves 5’432 full load hours under these conditions.

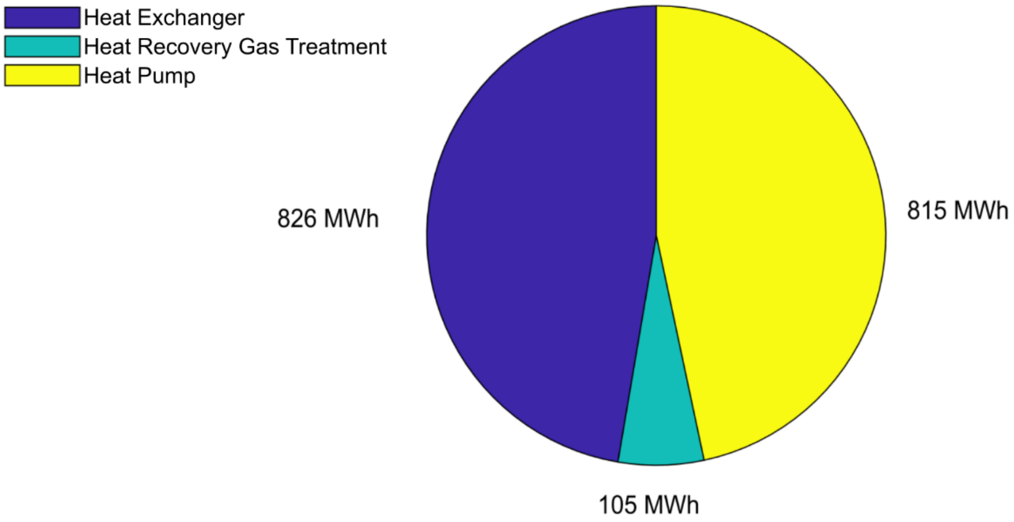

Figure 13. Shares of the different heating systems in the annual heat required for heating the digester .

3.3 Interim conclusion

As described in the last section, the combination of heat exchanger, recuperation from gas compression in gas treatment and heat pump shown is capable of supplying the required heat all year round - subject to the assumptions and simplifications made. In this case, the digestate storage temperature never falls below 7 °C, so there is also a certain safety margin. As a result, no additional heating would be required for normal operation. In the following, the sensitivities of the assumptions are checked for more broadly based conclusions.

3.4 Sensitivity analysis

A sensitivity analysis is carried out to check the reliability of the result ("No additional heating required in normal operation"). Table 3 shows the parameter variations carried out and the annual total shortfall after utilisation of the heat exchanger, heat recovery gas compression in gas treatment and heat pump. This corresponds to the necessary thermal energy that would have to be provided by an additional heating system.

With regard to the total heating requirement of 1’748 MWh/a, only the heat exchange with the environment is relevant. Unfortunately, this is probably where the greatest uncertainty exists, as this parameter was modelled relatively simplistically and depends on a number of factors, mainly the specific design of the digestate storage facility. The literature cited in section 2.4 provides a good insight into the potential complexity of this topic. It should be noted that a heat transfer coefficient of 10 $W/(m^2 \cdot K)$ can be deemed as relatively high (conservative).

Table 3. Parameter variations and cumulative missing heating energy ΔQ over the entire year per variation. Default values are highlighted in bold. The only variations with energetic deficits (red) are h = 5 or 10 W/(m^2 K) (heat transfer coefficient from the digestate storage to the environment) and Tmin = 9 °C (limit value for the temperature of the digestate storage). The amounts are to be compared with a total consumption of 1748 MWh/a.

Parameters	Unit	Variation						
η_{HEX}	-	0.4	0.5	**0.6**	0.7	0.8		
ΔQ	MWh	0	0	0	0	0		
h	W/(m^2K)	0.1	0.2	0.5	**1**	2	5	10
ΔQ	MWh	0	0	0	0	0	89.95	196.58
$\dot{Q}_{ga}$	kW	0	**12**	24				
ΔQ	MWh	0	0	0				
α_F	-	0.2	**0.3**	0.4	0.5			
ΔQ	MWh	0	0	0	0			
α_s	-	0	**0.15**	0.3	0.5			
ΔQ	MWh	0	0	0	0			
COP	-	3	**3.5**	4	4.5	5		
ΔQ	MWh	0	0	0	0	0		
$T_{min,d}$	°C	3	**5**	7	9			
ΔQ	MWh	0	0	0	5.09			
d	m	0.1	**0.2**	0.3	0.4	0.5		
ΔQ	MWh	0	0	0	0	0		

It is difficult to make a statement regarding the required output of this additional heating. In all simulations with shortfalls, the temperature limit in the digestate store is violated, causing the heat pump to be switched off. In this case, the missing output is that of the heat pump. However, as the digestate storage is a thermal reservoir with relatively high inertia, an additional (much smaller dimensioned) heating system can be switched on days or weeks before a predicted threshold value violation, which means that less heat has to be taken from the digestate storage. In this way, the threshold violation can be completely prevented. Alternatively, a variant is also conceivable in which the heat pump temporarily utilises the ambient air or exhaust air from the substrate hall as a thermal reservoir in order to prevent further cooling of the digestate or to generally operate in a more energy-efficient manner. This is associated with the installation of an additional air/water heat exchanger and a switching valve.

3.5 Further variations

In addition to the parameter variations presented, a variation of the heat consumption of the digesters was also analysed. This was done against the background that higher consumption is conceivable if an additional digester were to be built . In this case, the digestate storage would not be enlarged. This variation is combined with a variation of the mass throughput, as this can also change. These further variations are intended to cover uncertainties in the assumptions and demonstrate a certain flexibility of the concept. Table 4 shows the annual heating energy that would have to be provided by an additional heating system, depending on the respective combination of variations.

Table 4. Annual heating energy shortfall (MWh) with linear scaling of mass flow (1 = 39’806 t/a) and heating output (1 = 1’748 MWh/a).

Heat output		Mass flow 0.9	1.0	1.1	1.2	1.3
	0.9	0	0	0	0	0
	1.0	0	0	0	0	0
	1.1	5.6	0	0	0	0
	1.2	14.6	5.7	0.1	0	0
	1.3	25.0	14.3	5.5	0	0

Two conclusions can be drawn from this study:

- From an energy point of view, an increase in the mass flow has no influence on operation (as long as the required heat output is not affected)
- An increase in the required heat output is no problem, provided that the mass flow increases proportionally.

Overall however, even the most extreme result with an annual heating requirement of 2’270 MWh/a (1.3x nominal value) without a corresponding mass flow is relatively unproblematic, as the missing 25 MWh is only just under 1% of the annual heating requirement. On the one hand, this amount is smaller than modelling inaccuracies, and on the other hand, the problem can probably be solved through operational measures. This scenario would be conceivable in an extremely cold year, for example, in which the specific heating output required per mass flow increases or in the event of other unexpectedly high heat losses.

3.6 Comparison with other heat sources

The combination of heat pump, heat recovery and a heat exchanger shown in this study requires 232 MWh of electricity per year, but eliminates biogas consumption. This concept will be contrasted with a number of alternative concepts that reflect the status quo and/or best practices. These are:

- A gas boiler (efficiency 95%), which consumes biogas for heating the digester (concept 1). The use of gas heating is very suboptimal for this low-temperature application and is only listed here as a reference case.

- Combined heat and power plant (CHP), which supplies heat for heating the digester and simultaneously produces electricity that is not consumed locally (or not in the digester heating system). An electrical conversion efficiency of 30% and an overall efficiency of 90% are assumed (concept 2).

- Combination of CHP and heat pump (concept 3). In contrast to heating the digester with a CHP alone, the electricity generated here is used to operate a heat pump for additional heating of the digester with COP = 3.5.

- Combination of CHP, heat pump (see concept 3) and other efficiency measures (concept 4). Heat recovery and the substrate/digestate heat exchanger are also implemented here.

Figure 14 shows a comparison on an annual basis between the systems mentioned and the concept analysed in this study. This analysis does not provide any indication of the utilisation of the respective systems. For example, the CHP unit will have relatively few operating hours if it is coupled with a heat exchanger, heat recovery system and heat pump (concept 4). Nevertheless, some interesting insights can be gained from this analysis.

The most common comparative case of digester heating using a CHP (concept 2) is characterised by a very high gas consumption of 2'775 MWh/a, which corresponds to a self-consumption of 30.5 % - albeit with the simultaneous production of 749 MWh/a of electricity. If the electricity produced by the CHP is also used for digester heating by means of a heat pump, the plant can be operated with a self-consumption of 12.2 % (concept 3). If the efficiency measures highlighted in this report (heat recovery, gas compression and heat exchangers) are also used, the self-consumption drops to 5.7 % - with the proviso that this year-based analysis does not take into account any restrictions due to the high variability of the residual heating requirement in this case (according to the given heating outputs of the efficiency measures). This means that individual components are only used sporadically and therefore only have a few operating hours per year. Due to the technical complexity, this is likely to lead to very high investment and operating costs.

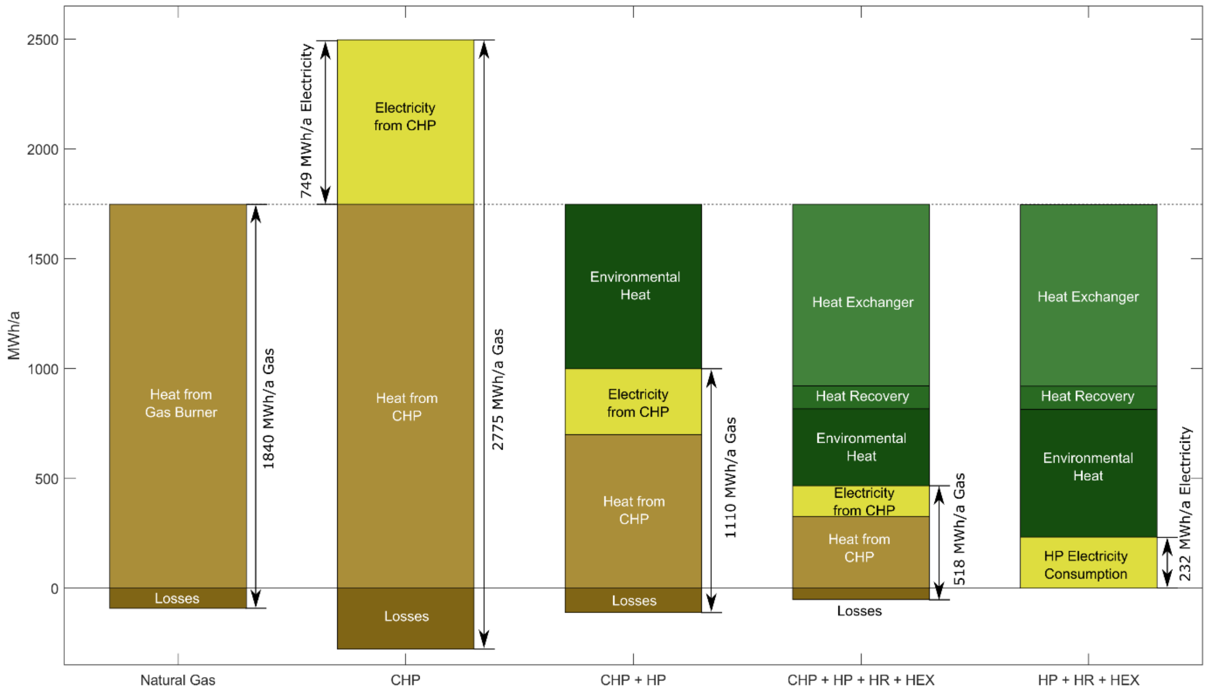

Figure 14. Comparison of different concepts for digester heating. There is an annual heating requirement of 1748 MWh (dashed line), which is covered by the various heat sources. The arrows to the right of the bars indicate consumption, while the arrow to the left of the bar indicates production.

Figure 15 shows the comparison of the annual net production of biomethane and electricity for the three variants gas boiler, CHP and heat pump + heat recovery + heat exchanger. Based on an annual biomethane production of 9.08 GWh (see Table 1) and a heating requirement of 1.75 GWh, this results in an annual biomethane production of 7.24 GWh for the variant with gas boiler, a biomethane production of 6.31 GWh and electricity production of 0.75 GWh for the variant with CHP, and a biomethane production of 9.08 GWh (100 % of the design volume) with an electricity consumption of 0.23 MWh for the variant presented here.

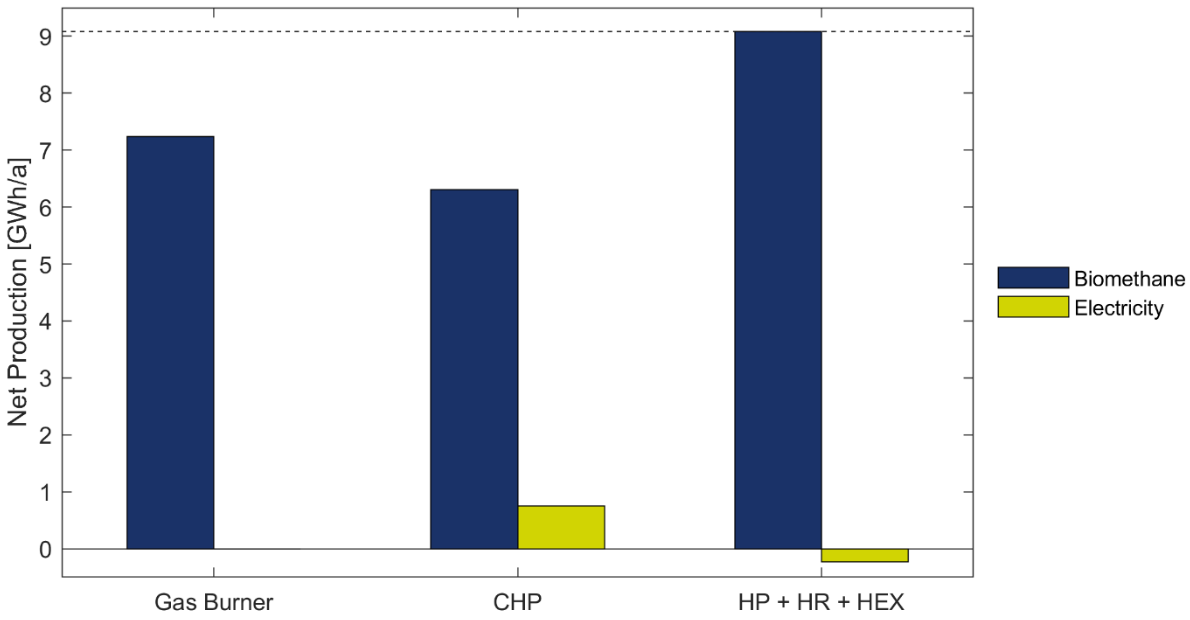

Figure 15. Comparison of the annual net production of biomethane and electricity of the planned biogas plant in Wittenbach using different heat sources for digester heating. Based on an annual biomethane production of 9.08 GWh, a gas boiler (95 % efficiency) requires 1.8 GWh as self-consumption, while a CHP has a biomethane consumption of 2.78 GWh - with simultaneous production of 0.75 GWh of electricity. In contrast, the combination of heat pump, heat recovery in gas compression, and the use of a substrate/digestate heat exchanger analysed in this study does not require any biomethane, but does require 0.23 GWh/a of electricity.

4 Conclusion

Using the planned biogas plant in Wittenbach as a case study, an energy concept for a direct feed-in biogas plant was developed, whereby an innovative combination of heat exchanger, heat recovery, and a heat pump was analysed. Under standard conditions (see Table 2), the result is a situation in which the entire heating requirement of the digesters can be covered throughout the year exclusively by the heat exchanger, heat recovery and the heat pump. The critical value of the minimum digestate storage temperature (5 °C) is not violated in this case, but is maintained with a margin of >2 °C.

In a sensitivity analysis, various aspects of the modelling and assumptions were examined in more detail in order to quantify their influence on the results. Selected parameters were varied to a certain extent for this purpose. It was found that there is a considerable margin in most cases. Problematic combinations were particularly evident in the case of high heat exchanges between the digestate storage and the environment and greatly increased heating requirements without a correspondingly higher mass flow rate. While the first problem (poorly insulated digestate storage) can be prevented by appropriate construction, the second problem (e.g. very cold year, unexpected heat losses) is more difficult to solve, but is also reduced by good insulation.

The simulations show that no additional heating is required for normal operation of the system in the state modelled here, except for redundancy considerations and for start-up. The required technologies are each tried and tested on their own and are already being used successfully by our implementation partners. The realisation of the biogas plant in Wittenbach and the knowledge gained from its operation will provide extensive data to validate the model presented here. In addition, the field tests will provide the opportunity to calibrate various model parameters, most of which currently consist of literature data and conservative estimates. The intention is to make the model (after validation/calibration) available to industry in a suitable form.

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