

## Improving the Energetic Self-Sufficiency of Waste Water Treatment Plants – Tool for Needs-based Configuration of the Thermal Sludge Gasification Process

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1.	Description of a sludge gasification process and applications .....	444
2.	Modelling the waste water treatment plant .....	446
2.1.	Step one: Configuration of the Model Plant .....	447
2.2.	Step two: Configuration of the energy network system in the Model Plant.....	447
3.	Summary .....	453
4.	References .....	453

In 2017 the German sewage sludge ordinance (AbfKlärV) was amended to include a phased-in requirement for the recovery of phosphorus from sewage sludge commencing in 2029 [7]. Furthermore, regulations for the land application of sewage sludge are becoming more stringent in Germany. Decentralized sludge gasification on-site is an attractive option for producing a practically carbon-free ash containing the total phosphorus content of the original sludge. The ash can subsequently be used as a feedstock for the production of fertilizers e.g. in centralized fertilizer production facilities. This approach avoids sludge tourism and the associated environmental impact: Compared to dewatered sludge which is typically disposed of off-site, the ash remaining after gasification represents a mass reduction of approximately 92 %. Furthermore, energy is generated for on-site consumption in the waste water treatment plant (WWTP) and can contribute towards offsetting consumption of heat and power from external sources.

In the development of a decentralized sludge valorization concept, sludge gasification applications are integrated and evaluated within existing WWTP infrastructure. Here the goal should be to configure the process in such a manner that synergies in the energy network are optimally exploited. Since the WWTP is a complex system with many interacting factors, a holistic approach is necessary. In order to simplify this task, Montanuniversität of Leoben was commissioned to develop a simulation *model* based on configurable modular building blocks. The Excel-based tool called *Optievlex* uses standard databases for default process parametrization and calculations as long as modules have not been supplemented with plant-specific values. Thus the tool can offer either an approximate model of the process with minimal user input, or a detailed site-specific process model where more user input is required.

While *Optievlex* can currently just be applied as a non-time-resolved modelling tool, a time-resolved modelling tool is at present under development.

Here an approach is described to modelling an anaerobic WWTP with a capacity of 300,000 PE (Population Equivalent) and exploring three configurations of the internal energy network. All three configurations explored include *sludge gasification* as a core process and range from heat-focused to electricity-focused solutions. The motivation is to explore the configuration which offers the optimal degree of energetic self-sustainability i.e. minimizing external sources of heat and power.

## 1. Description of a sludge gasification process and applications

Kopf SynGas GmbH & Co. KG offers technology for the thermal gasification of sewage sludge. Solutions are based on scalable modules ranging from throughput capacities of 1,000 t DS/a to 15,000 t DS/a (about 60,000 to 900,000 PE). The core process is a stationary bubbling fluidized bed gasifier generating a combustible synthesis gas. The energetic valorization of the synthesis gas can be configured to focus on heat production (the so called *Heat Module*, Figure 1) or electricity production (*CHP Module*, Figure 2) according to on-site energy requirements.

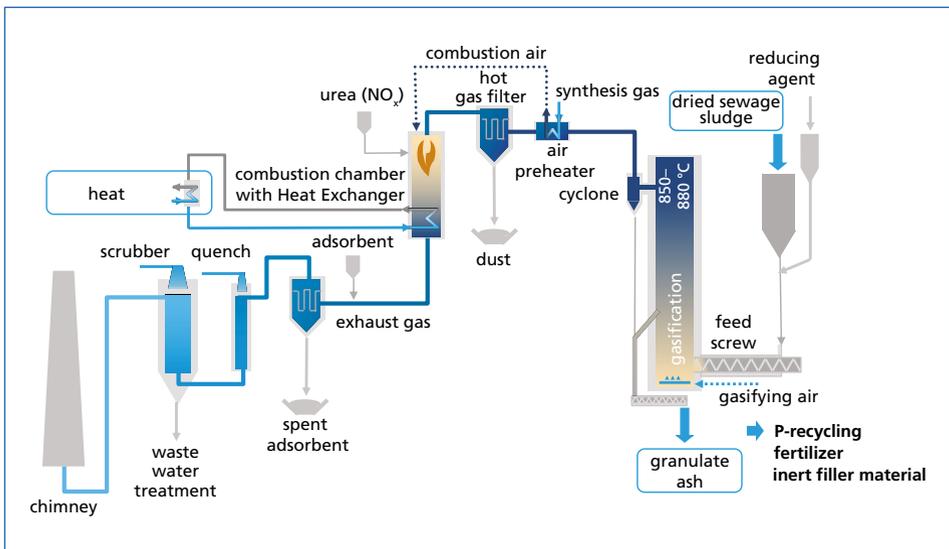


Figure 1: Heat Module of the sludge gasification process

As an input, the process accepts digested or undigested sewage sludge dried to a DS content of min. 85 %. The gasification process in the fluidized bed is autothermal – no auxiliary fuels are required in operation. When a sludge belt dryer with a sludge distributor is employed in the sludge drying process, a dried sewage sludge granulate can be generated. This product with a well-defined particle size distribution and low dust quantities is particularly suited for the bubbling fluidized bed. Belt sludge dryers

can typically be configured with LT- (low temperature e.g. Water, 90 °C) or HT- (high temperature e.g. Water 140 °C) heat supplies, or even as a series of HT- and LT-segments e.g. belt dryers of Sülzle Klein GmbH.

In the gasifier the organic fraction of the dried digester sludge is converted to the gas phase at about 870 °C, slight positive pressure (< 500 mbar (g)), and sub-stoichiometric conditions (Lambda about 0,3). The resulting combustible synthesis gas has a lower heating value of about 3.4 to 5.5 MJ/kg with higher heating values for aerobic sludges compared to anaerobic sludges. Ash granulate (resembling the originating sludge granulate in geometry and reduced in size) is removed continuously from the gasifier in operation. About 70 mass-% of the ash in the sludge is removed as ash granulate, while the remaining 30 mass-% is removed as dust predominantly in the cyclone (25 mass-%) and to a lesser extent in the hot gas filter (5 mass-%).

With the Heat Module and CHP Module, gas de-dusting takes place in the synthesis gas phase. The main difference is that gas cleaning in the Heat Module is carried out post combustion, while the gas cleaning in the CHP Module is carried out prior to combustion. Furthermore, the CHP Module is equipped with a two stage gasifier (thermolysis screw followed by fluidized bed gasification) to minimize tar generation (this is not necessary for the Heat Module since synthesis gas is combusted in a boiler as opposed to a gas engine). Another variant of the Heat Module is the Heat Module with ORC (Organic Rankine Cycle). Here a portion of electricity can be generated in addition to heat. The main difference in the quality of the heat is that the heat carrier in the Heat Module is HT-Water at 140 °C, while the heat carrier in the Heat Module with ORC is LT-Water at 90 °C.

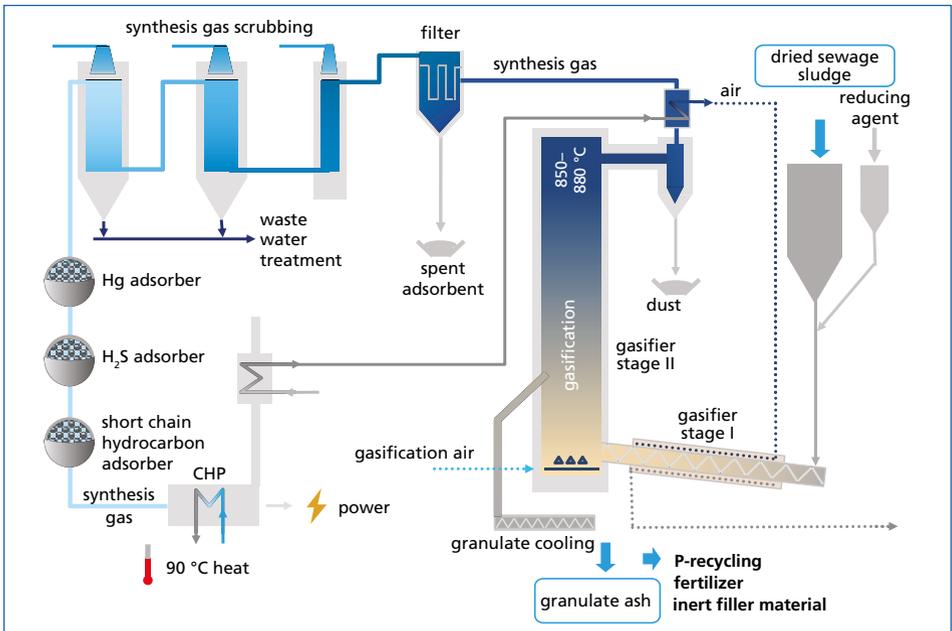


Figure 2: CHP Module of the sludge gasification process

Sewage Sludge

## 2. Modelling the waste water treatment plant

An approach to using the modelling tool has previously been described [6]. To determine the effect of a sludge valorization plant on the overall energy balance of a municipal WWTP, it is firstly necessary to estimate the sludge output of the process train as well as the energy requirements of sludge drying units and the energy production of sludge valorization units. The annual sludge quantity and its energy content as well as the mass and energy flow of the digester gas were estimated using *Optievlex*. The generated data was used for further calculations to determine the energy consumption of suitable drying systems as well as the energy production of different gasification units. Here adjusted data from existing industrial installations are used rather than the standard value settings in the Tool.

The Excel-based static modular tool enables the generation of mass and energy balances of WWTP configurations defined by the user. State of the art preliminary (e.g. screening, grit removal), primary (e.g. sedimentation), secondary (e.g. aerobic and anaerobic treatment) and tertiary (e.g. nitrification, denitrification, phosphorus removal) treatment technologies can be combined to technologically compatible process trains. Furthermore, the tool includes digester gas and sewage sludge valorization modules like sludge drying units, CHP-units or sludge gasification units.

For this analysis, a typical system configuration for Austria and Germany with a capacity of 300,000 PE has been chosen (hereafter referred to as *Model Plant*).

The configured process train of the Model Plant used in this study is presented in Figure 3 below.

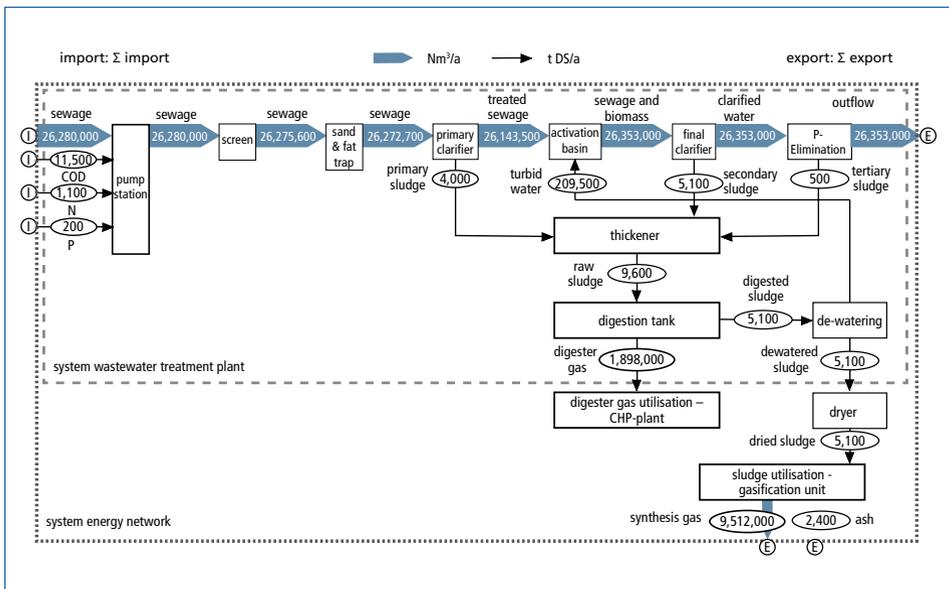


Figure 3: The configured process train of the Model Plant used in this study

The boxes (building block modules in the tool) represent the treatment technologies integrated in the Model Plant. The modules can be further specified by setting parameters like the operating hours, rated power or efficiency. The black arrows illustrate mass flow, which connect the single processes to a process train, while the blue arrows indicate volume flow.

## 2.1. Step one: Configuration of the Model Plant

The capacity of the WWTP was set at 300,000 PE, with a dry weather flow of 240 l/(PE·d) (the tool predicts COD and BOD<sub>5</sub> values of about 436 mg/l and 218 mg/l respectively). The *primary clarifier*, *activation basin*, *primary clarifier* and *digestion tank* are selected due to the fact that, in Germany and Austria, plants with a capacity of > 50.000 PE are generally biological treatment plants with anaerobic stabilization (> 90 %) [1, 2]. The modules *screen*, *sand & fat trap*, *thickener* and *dewatering unit* are typical components of modern treatment plants to guarantee an adequate purification. To meet effluent emission limits, the module *P-Elimination* (with iron salts) was integrated into the Model Plant [4].

Raw sludge is made up of primary sludge, surplus secondary sludge, and tertiary sludge which is pre-thickened before the digestion. The sludge digestion process was configured as a mesophilic type with a sludge treatment time of 25 days. The addition of co-substrate was not considered in this modelling application. With the described configuration, 5,105 t DS/a of raw sludge were projected after post-thickening. This corresponds to a specific digester sludge production of 17 kg/(PE·a). The approximate make-up of the raw sludge is about 42 mass-% primary sludge, 53 mass-% surplus secondary sludge, and 5 mass-% tertiary sludge. In practice, tertiary sludge is usually considered to be a component of the surplus secondary sludge. The predicted mass fractions making up the raw sludge are typically values for German WWTPs [5]. In the sludge digestion process, the digester gas yield was estimated at 5,202 Nm<sup>3</sup>/d. After dewatering the digested sludge with a screw press, the estimated dry solids content was 26 % DS.

## 2.2. Step two: Configuration of the energy network system in the Model Plant

In the second step, the modules *digester gas valorization*, *sludge drying* and *sludge valorization* need to be selected and the relevant operating parameters defined. In the accompanying discussion, the following abbreviations are used to refer to heat quality:

- HT or High Temperature refers to water at 140 °C as an energy carrier;
- LT or Low Temperature refers to water at 90 °C as an energy carrier;
- LT70 or Low Temperature 70 referring to water at 70 °C as an energy carrier.

The heat quality can refer to a pre-requirement of a module e.g. a HT-Belt dryer requires water at 140 °C as a heat source, or the output of a process e.g. the heat produced in an ORC is transferred to LT-water at 90 °C which acts as a heat carrier.

## Energy potential in the WWTP

The composition of the sludge is approximated by comparing the estimated composition after the waste water treatment process with that of pre-defined standard sludge types and making a best-match assignment. The assigned composition is shown in Table 1 below and was used for subsequent sludge gasification calculations.

For the described gasification applications, the sludge is dried to 90 % DS. A belt dryer was selected here for the reasons described in section 1. In all three applications that follow, digested sludge is converted to synthesis gas in a fluidized bed reactor. Table 2 shows the energy potential of the WWTP energy network before digester gas and synthesis gas valorization.

### Configuration of an energy network including a Heat Module

For this configuration, the total volume of digested gas produced is combusted in a CHP unit. When a boiler is configured as a synthesis gas valorization aggregate, 11,196 MWh/a of heat is available for external use. Since the heat can be made available at high temperatures e.g. water, 140 °C, selection of a HT-Belt dryer is recommendable. The main advantages here over a LT-Belt dryer are a smaller footprint, a lower specific electrical consumption, and the possibility of recovering low temperature heat for e.g. tempering of the digester towers or heating administration buildings on-site.

The heat balance of the Model Plant with this configuration is shown in Figure 5. Here, a heat surplus exists. In Figure 10, the heat energy flows and their quality are shown in more detail, allowing for a better interpretation of the results and optimization of the system through a pinch analysis. The first step is to satisfy the demand of the HT-belt dryer with HT-heat. Since the heat demand is 11,479 MWh/a, the requirement

Table 1: Predicted composition of the dried digested sludge

Digested sewage sludge	Unit	Value
Ash	m.-%, DS	47
Phosphorus <sup>1)</sup>	m.-%, DS	3.1
Carbon	m.-%, DS	27
Oxygen	m.-%, DS	17
Hydrogen	m.-%, DS	4
Sulphur	m.-%, DS	1
Nitrogen	m.-%, DS	4
Lower heating value	MJ/kg DS	11.3
Annual sludge quantity	t DS /a	5,105
Annual energy potential, a.r. <sup>2)</sup>	MWh/a	15,691

<sup>1)</sup> Phosphorus is a component of the ash

<sup>2)</sup> a.r. = as received i.e. 90 % DS

Table 2: Energy potential of the WWTP energy network

Digester gas	Unit	Value
Methane content	vol.-%	65
Lower heating value	kWh/Nm <sup>3</sup>	6.48
Daily volume flow	Nm <sup>3</sup> /d	5,202
Annual energy potential	MWh/a	12,305
Synthesis gas		
Composition		
Nitrogen	vol.-%	48.4
Carbon Monoxide	vol.-%	9.8
Carbon Dioxide	vol.-%	12.3
Methane	vol.-%	2.4
Hydrogen	vol.-%	14.9
Water	vol.-%	11.0
Lower heating value <sup>1)</sup>	kWh/Nm <sup>3</sup>	0.970
Synthesis gas, daily volume <sup>2)</sup>	Nm <sup>3</sup> /d	28,527
Synthesis gas firing capacity <sup>2)</sup>	kW	1,153
Annual energy potential (chemical)	MWh/a	9,223
Annual energy potential (chemical + latent)	MWh/a	12,905

<sup>1)</sup> This is a corrected value required in the mass and energy balance of the gasifier. The calculated LHV for this synthesis gas based on the gas composition is 1.06 kWh/Nm<sup>3</sup>.

<sup>2)</sup> Based on 8,000 h/a gasifier operation

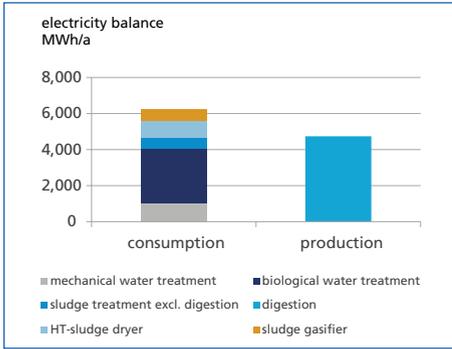


Figure 4: Electricity balance of the Model Plant with Heat Module solution

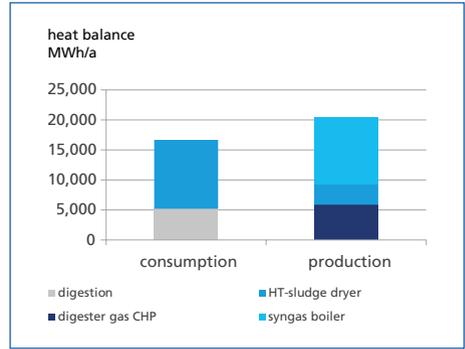


Figure 5: Heat balance of the Model Plant with Heat Module solution

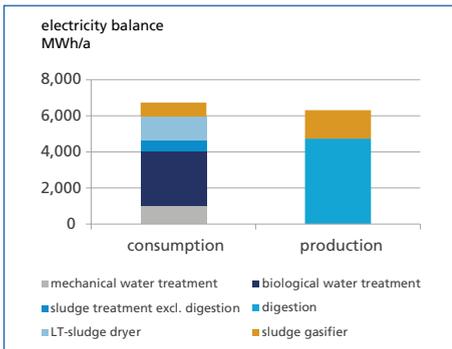


Figure 6: Electricity balance of the Model Plant with Heat Module + ORC solution

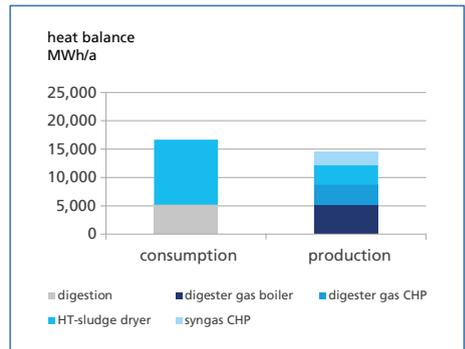


Figure 7: Heat balance of the Model Plant with Heat Module + ORC solution

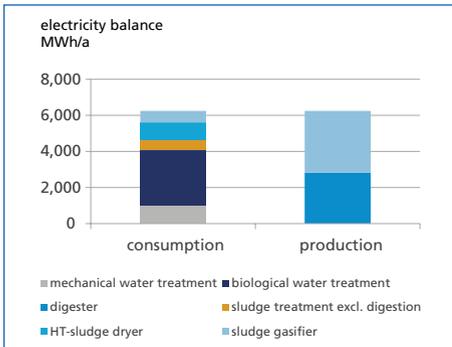


Figure 8: Electricity balance of the Model Plant with CHP Module solution

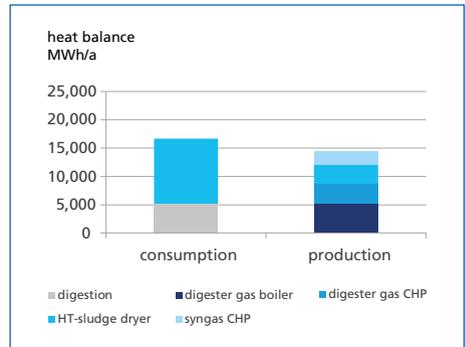


Figure 9: Heat balance of the Model Plant with CHP Module solution

of the dryer is almost covered solely from the synthesis gas boiler. HT-heat from the exhaust gas of the digester gas CHP engine is also available to cover the heat deficit. In the sludge dryer, recovery of the energy in the exhaust gas generates 3.444 MWh/a of

LT70-heat, which in turn can be used to cover a large portion of the heat demand of the digester tower. The shortfall of 1,753 MWh/a can be supplied by HT-Heat, leaving a surplus of 1,526 MWh/a HT-heat. This could be used to puffer process fluctuations e.g. changes in the DS content of the dewatered sludge, sludge composition etc. The choice of a HT-belt dryer lowers the electricity demand compared to a LT-belt dryer. This is advantageous, especially since an electricity deficit exists (Figure 4). Considering an electricity price of 0.2 EUR/kWh [3], the annual electricity costs are 302,400 EUR.

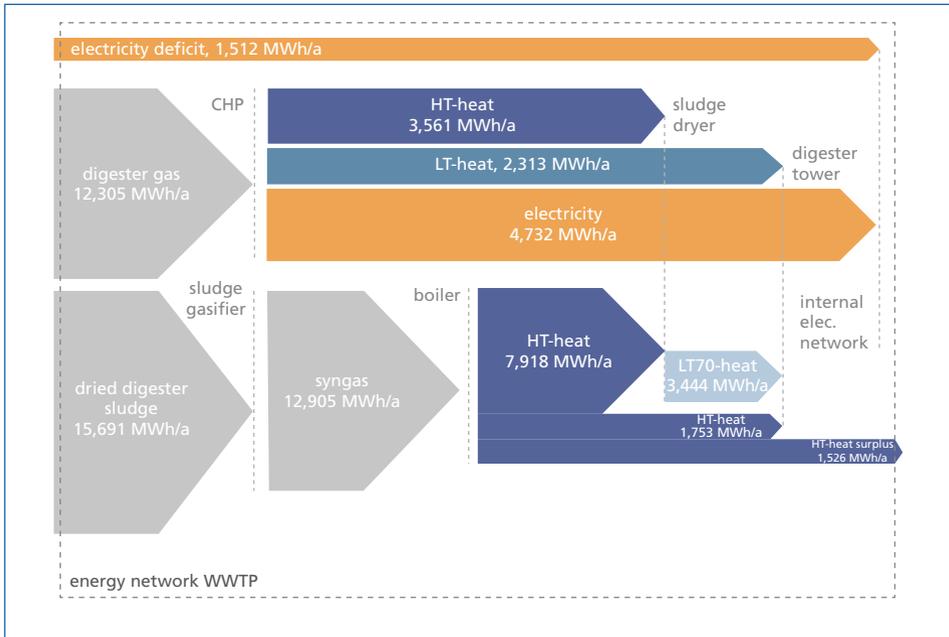


Figure 10: Energy flows within the energy network of the Model Plant for the Heat Module application

### Configuration of an energy network including a Heat Module + ORC

As in the *Heat Module* configuration, the total volume of digester gas is combusted in a CHP unit. When a boiler for synthesis gas is coupled with an ORC, approximately 7,692 MWh/a heat and 1,581 MWh/a electricity are produced. In terms of available heat sources for sludge drying, predominantly LT-heat from the synthesis gas boiler ORC and LT-heat from the digester gas CHP motor are available. A smaller portion of HT-heat from the digester gas CHP is also available. For this reason an LT-dryer was selected for simplicity, though in practice a belt dryer with a mixture of HT- and LT- segments could also be considered. For the LT-belt dryer, waste heat cannot be viably recovered since the exhaust gas temperature is too low.

As can be observed in Figure 6 and Figure 7, both an electricity deficit and a heat deficit exist. In Figure 11 the energy flows in the network are shown. After satisfying the heat demand of the dryer with a mixture of HT- and LT-heat from the digester gas CHP as well as LT-heat from the synthesis gas boiler ORC, a surplus of 2,087 MWh/a LT-heat

is available which could in turn be used for tempering the digester tower. Nonetheless a total of 3,108 MWh/a of LT70-heat needs to be supplied from external sources to the digestion tower. Compared to the *Heat Module* solution, the *Heat Module + ORC* the electricity deficit is reduced by approximately two thirds, the opportunity cost being a heat deficit which did not exist for the Heat Module configuration. Taking standard DWA values of 0.2 EUR/kWh for electricity and 0.1 EUR/kWh for heat, the annual energy costs are 391,000 EUR.

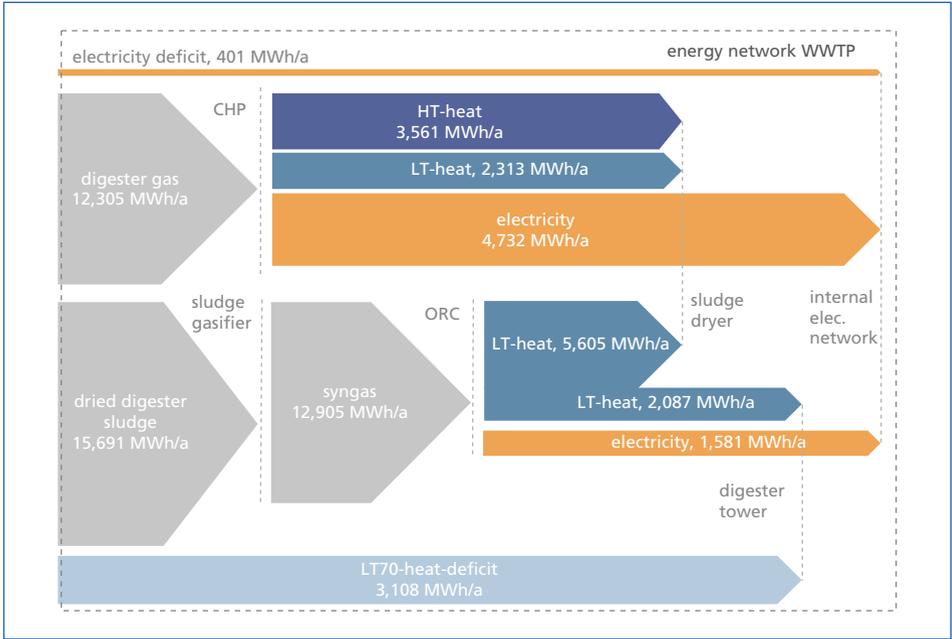


Figure 11: Energy flows within the energy network of the Model Plant for the Heat Module + ORC application

*Configuration of an energy network including a CHP Module*

Figure 8 and Figure 9 show the overall respective electricity and heat balances of the Model Plant with CHP Module for synthesis gas valorization. The configuration was optimized in several iterations. The starting point was to combust all the digester gas in a CHP engine, as well as all the synthesis gas in a CHP engine. A LT-belt dryer was selected since predominantly LT-heat was available from the CHP engines (the HT-heat from the synthesis gas CHP is required for the thermolysis screw in the first gasification stage). With this configuration it was evident that a large electricity surplus existed, while a large heat deficit existed. In order to reduce the electricity surplus and the heat deficit, a portion of the volume flow of digester gas is diverted to a digester gas boiler. With this configuration, a greater portion of HT-heat is generated in the energy network. Since changing the dryer to a HT-belt dryer would mean further reductions in electricity consumption and the possibility of exploiting cascading energy effects (i.e. recovery of heat from the exhaust gas), this optimization was executed (Nonetheless

a deficit of 4,135 MWh/a of HT-heat exists). The portion of digester gas diverted from the CHP engine to the boiler is increased to account for the lower electricity demand of the HT-belt dryer. In this case the digester gas volume flow to the CHP and boiler was set so that the electricity production equals the electricity consumption. In practice the configuration of the energy network would take other factors into consideration like dynamic load profiles in the WWTP, required safety puffers for electricity production etc. - the purpose of the energy network configuration used here is to show its general characteristics and capabilities. When the LT70-heat from the belt dryer exhaust gas is bundled with the LT heat from the digester gas CHP and synthesis gas CHP, the heat demand of the digester tower can be satisfied.

A LT-heat surplus of 1,927 MWh/a for this configuration exists. Since a HT-sludge dryer has been configured in this case, the surplus heat cannot be used to directly offset the external heat demand since it does not have the required quality. However, the possibility of configuring the sludge dryer with a LT-segment could be investigated in a further optimization iteration in order to offset the HT-heat deficit. Considering this optimization (and that the electricity consumption remains the same), the annual heat costs are approximately 220,800 EUR.

Figure 12 shows the energy flows in the energy network of the WWTP configured with a CHP engine for synthesis gas valorization after several optimization iterations.

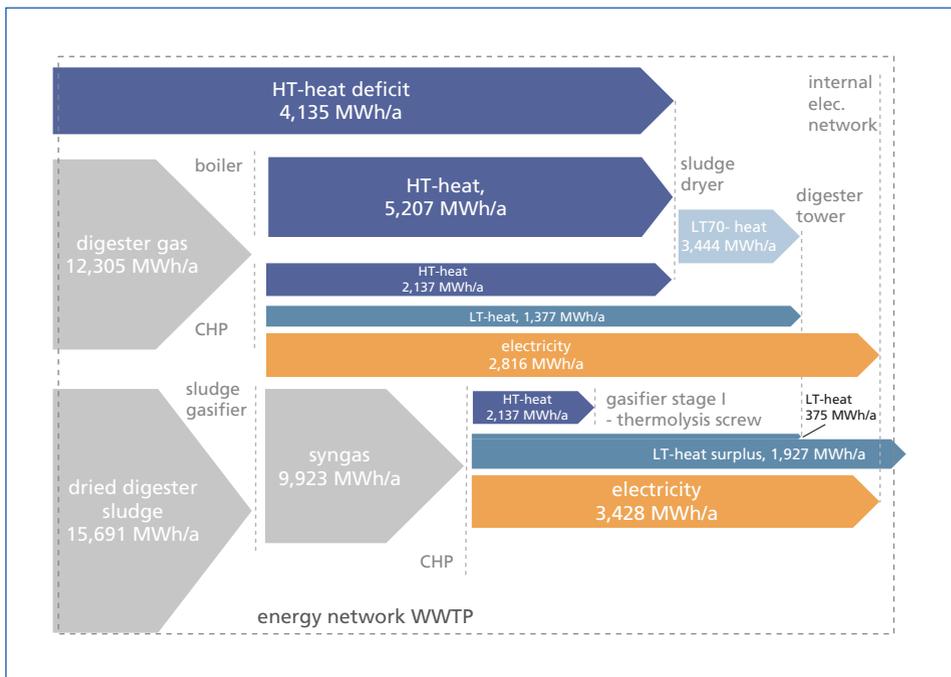


Figure 12: Energy flows within the energy network of the Model Plant for the CHP Module application

### 3. Summary

The configuration of a non-time-resolved WWTP model with an anaerobic sludge stabilization and capacity of 300,000 PE in the *Optievlex* modelling tool and the configuration and optimization of the WWTP energy network was described. In the tool, the process train can be easily assembled and the system holistically evaluated, including intermodule influences.

The model predicted a digester sludge quantity of 5,105 t DS/a (about 17 kg DS/(PE·a)) with an ash content of 47 mass-% and a lower heating value of 11.3 MJ/kg DS. Three energy network configurations were compared, 1) digester gas combustion in a CHP unit plus a HT-belt dryer for sludge drying and a synthesis gas boiler 2) digester gas combustion in a CHP engine plus a LT-belt dryer for sludge drying and a synthesis gas boiler fitted with an ORC, and 3) digester gas combustion in a CHP engine and digester gas boiler, plus a HT-belt dryer for sludge drying and synthesis gas combustion in a CHP engine. Where possible, synergies in the energy network were exploited based on a pinch analysis and energy cascading effects. In terms of annual energy costs, the CHP module performed best for this WWTP configuration (220,800 EUR), followed by the Heat Module (302,400 EUR) and finally the Heat Module + ORC (391,000 EUR), based on prices of 0,10 EUR/kWh for heat and 0,20 EUR/kWh for electricity. The quality of the of the heat deficit should also be considered – for the CHP module configuration, a HT-heat deficit exists, while for the Heat Module + ORC, a LT70-heat deficit exists. In a more detailed economic evaluation, CAPEX and OPEX factors can be explored and evaluated. Further variants and optimization iterations can be carried out to explore optimal exploitation of energetic synergies in the energy network.

Other critical factors need to be taken into account in the selection of the optimal energy network configuration, the main ones being the time-resolved load profiles in the WWTP and the expected flexibility of the energy network. Monthly variations in the sewage sludge composition based on factors within and outside the WWTP system boundary should also be monitored and evaluated.

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Bibliografische Information der Deutschen Nationalbibliothek

Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über <http://dnb.dnb.de> abrufbar

Thiel, S.; Thomé-Kozmiensky, E.; Winter, F.; Juchelková, D. (Eds.):

**Waste Management, Volume 8**  
– Waste-to-Energy –

ISBN 978-3-944310-42-8 Thomé-Kozmiensky Verlag GmbH

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Publisher: Thomé-Kozmiensky Verlag GmbH • Neuruppin 2018

Editorial office: Dr.-Ing. Stephanie Thiel, Dr.-Ing. Olaf Holm,  
Elisabeth Thomé-Kozmiensky, M.Sc.

Layout: Janin Burbott-Seidel, Ginette Teske, Roland Richter, Sarah Pietsch,  
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Printing: Universal Medien GmbH, Munich

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