'Hot topic' – combined energy and process modeling in thermal hydrolysis systems

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ABSTRACT

The thermal hydrolysis process (THP) is applied to enhance biogas production in anaerobic digestion (AD), reduce viscosity for improved mixing and dewatering and to reduce and sterilize cake solids. Large heat demands for steam production rely on dynamic effects like sludge throughput, gas availability and THP process parameters. Here, we propose a combined energy and process model suitable to describe the dynamic behaviour of THP in a full-plant context. The process model addresses interactions of THP with operational conditions covered by the AD model obeying mass continuity. Energy conservation is considered in balancing and converting various energy species dominated by thermal heat and calorific energy. The combined energy and process model was then applied on the THP at Blue Plains advanced WWTP (DC Water) to analyse the process and assess potential energy optimizations. It was found that dynamic effects like mismatched steam production and consumption, temporary gas shortages and underloaded units are responsible for energy inefficiencies with losses in electricity-production up to 29%.

Key words | energy balance, energy model, process model, thermal hydrolysis process, whole plant model

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INTRODUCTION

Thermal hydrolysis of sludge prior to anaerobic digestion (AD) has become a well established method to reduce viscosity, improve pathogen inactivation, digestion and dewatering performance (Ruffino *et al.* 2015) on wastewater treatment plants (WWTP). The heat to maintain process temperatures of 150 °C and higher in pressurized vessels can be provided from combined heat and power generation (CHP). Reduced viscosity enables digesters to be operated at high solids concentrations for the sake of digester volume reduction, while improved gas production and dewatering characteristics lead to decreased sludge cake quantities (Carlsson *et al.* 2012). Heat can be provided by utilization of methane out of the AD process.

Gas engines are commonly used on conventional WWTP plants (without thermal hydrolysis process (THP)) due to their high electric efficiency. Heat out of CHP is usually abundant for digester and building heating. The heat supply from gas engines is partly available as high temperature heat (HT) from the exhaust gas (>180 °C) and low temperature heat (LT) from cooling cycles (<100 °C). Both streams are usable for LT-heating like digester heating. Although THP is known to improve the net heat balance of the sludge system (Haug *et al.* 1978; Pinnekamp 1989), pretreatment systems like those from Cambi® require most of the heat at HT-Levels since live steam is used as a heat carrier. Therefore, heat for evaporation at steam temperature (approx. 180 °C) determines the total heat demand. Consequently, mainly high temperature fractions can be used for steam generation in THP. WWTPs with THP are therefore likely to face HT heat shortages. Gas turbines, with lower electric efficiencies, offer the entire heat at exhaust temperature which is why much larger portions of high temperature heat can be supplied compared to gas engines. As a third alternative, gas burners can supply the largest portions of high temperature heat, however, without electricity production (Martens 1998). The most efficient system, combination of systems or control scheme depends on the total heat balance, THP parameters and dynamics of the whole plant. Especially under dynamic situations, this is not trivial. When modelling a THP, both process

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kinetics and energy issues must be addressed since either may determine the efficiency of the process. The dynamics of combined energy and process models and evaluations of potential improvements within the THP process was demonstrated on the advanced WWTP Blue Plains (Washington, DC, USA).

Energy and process interference

High solids digestion as a method to reduce heat demands and increase sludge retention times goes along with high viscosities and all related problems like pump failure, mixing problems (Ratkovich *et al.* 2013) and mass transfer limitations (Abbassi-Guendouz *et al.* 2012). Furthermore, high solid digestion also leads to high ammonia concentration and potential ammonia inhibition (Haug *et al.* 1978; Wett *et al.* 2014). Heat shortages might lead to reduced reactor temperatures. Xue *et al.* (2015) mentioned that both treatment temperature and reactor retention times strongly affect THP performance in regards to viscosity reduction, biogas yields and dewaterability.

Energy issues will therefore strongly interfere with process dynamics and vice versa which can only be described by comprehensive and coupled process and energy models.

METHODS

WWTP blue plains

Blue Plains is a 3-sludge plant with chemically enhanced primary treatment (CEPT) capturing approximately 50% of influent chemical oxygen demand (COD) within primary sludge. Additional COD reduction takes place in the secondary sludge system at relatively short sludge retention time (SRT) of 1.5–2.0 days. Then downstream in a higher SRT-system nitrification in followed by a post-denitrification process involving methanol dosing (tertiary sludge system). Prior to final discharge, the water is sand-filtered and disinfected. At the current flows of 1,100 megaliters per day (MLD), approximately 300 tons per day of primary- and biological solids are thickened to 5% total solids (TS), blended, screened, and then dewatered to 16.0% TS for feed to the Cambi®-THP.

The THP at Blue Plains consists of four parallel trains, each with a pulper, six batch reactors, and a flash tank (Kepp *et al.* 2000). The reactor is heated by live steam at 180–190 °C to achieve a reactor temperature of 155–165 °C at a retention time of 30 min within the reactor. Afterwards, the sludge gets depressurized within the flash tank. A small excess pressure (corresponding to the steam pressure at 107 °C) within the flash tank is maintained intentionally to establish a driving force to transport the recycle steam out of the vessel. The spontaneous evaporation causes strong forces which disintegrates the sludge. The resulting steam is then recycled to the pulper to preheat the feed sludge or it gets discharged as waste steam through steam dump condensers. The hot sludge out of the flash tank must be cooled down to digestion temperature before it is fed to AD.

The system is designed for larger sludge throughputs than the average amount to keep reserves for load peaks and future demands. The CHP facility of Blue Plains includes three gas turbines (Mercury 50 by Solar® Turbines) to generate heat and electricity. Steam for the THP is produced by using the turbine exhaust within heat recovery steam generators (HRSG). Additional duct burners are used to supplement the heat to each HRSG to meet temporary high steam demands. Data for this study was ascertained from historical full plant measurements within a period of one year (July 2016–June 2017).

AD- and THP-process model

While primary sludge is considered as easily degradable, secondary sludge, which consists mainly of biomass out of the activated sludge process, often shows lower degradation rates. Slow degradability for biomass can be attributed to an active protection of biomass against enzymatic attacks by building up extracellular polymeric substances (EPS) (Appels *et al.* 2008). The process of AD can be modelled as a four-stage process (see Figure 1). When biomass (X_{Bio}) decays, its organic content becomes partly available for enzymatic reactions – particulate biodegradable substrate (X_B), while another portion of endogenous decay products (X_E) is hardly degradable (Henze *et al.* 2000; Batstone *et al.* 2002). Decay is often described by a first order kinetic (Batstone *et al.* 2002). The different degradability of primary and secondary sludge can be addressed by different initial X_B/X_{Bio} fractions.

X_B is then processed by hydrolysis which can be modelled as a conversion of X_B to dissolved readily biodegradable substrate (S_B), accompanied by ammonia and phosphate release (Wett *et al.* 2009; Xue *et al.* 2015). Hydrolysis is either modelled as first order kinetic like in ADM 1 (Batstone *et al.* 2002), neglecting the influence of hydrolysing biomass or by addressing the role of biomass vicinity as described by the Monod-ratio saturation function in ASM 1 (Henze *et al.* 2000; Vavilin *et al.* 2008). Before

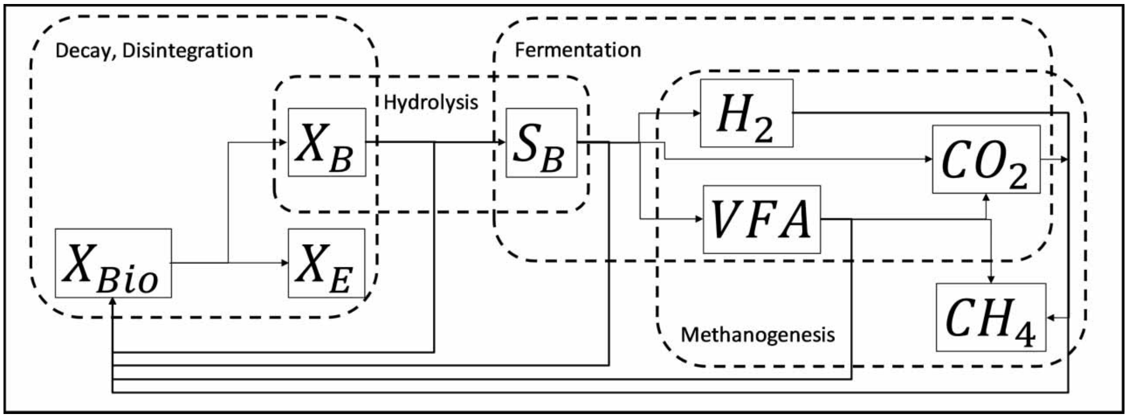

Figure 1 | Process-scheme of anaerobic digestion of biomass.

being available for methanogenesis, S_B needs to be further processed to volatile fatty acids (VFA) for acetoclastic methanogenesis, to hydrogen (H_2) and carbon dioxide (CO_2) for hydrogenotrophic methanogenesis (Batstone *et al.* 2002). This step is described by the process of S_B-fermentation with a Monod-saturation function for S_B and a first order kinetic for biomass. All stages, except decay/disintegration, are catalysed by biomass which results in growth of X_{Bio}.

THP targets a sterilizing process where biomass is completely inactivated and substrate availability is increased (Ruffino *et al.* 2015). Sterilization takes the same pathway as decay. Therefore, sterilizing pre-treatment processes like THP can be understood as a complete decay or disintegration. The increased substrate availability is a result of this shift towards X_B.

THP also aims to perform a quick hydrolysis which is often considered as the rate limiting step in AD and can be expressed as a shift from X_B towards S_B. Since hydrolytic reactions still prevail in AD of processed sludges (Vavilin *et al.* 2008), the hydrolytic shift must be considered incomplete. This shift is known to be influenced by reaction temperatures as shown by studies on COD solubilization in THP systems with resulting portions of soluble COD versus total COD of 30.8% at 160 °C (Wett *et al.* 2009).

Moreover, hydrolysis rates in digesters downstream of the THP-system are also reported to be increased due to a better accessibility of hydrolytic enzymes on the enlarged substrate surface (Vavilin *et al.* 2008) and better mass transfer as an effect of viscosity reduction (Ruffino *et al.* 2015; Xue *et al.* 2015) and hence support high solids digestion. Equation (1) shows the hydrolysis rate model (μ) as proposed by Henze *et al.* (2000) and Vavilin *et al.* (2008). Obviously, THP converts X_{Bio} into X_B and, therefore, in the consecutive digester, X_B/X_{BIO} gets maximized which pushes hydrolysis towards saturated rates.

$$\mu = \mu_{max} \cdot X_{Bio} \cdot \frac{X_B/X_{Bio}}{X_B/X_{Bio} + K_{hyd}} \tag{1}$$

The hydrolysis rate can be increased either by increasing μ_{max} or by reducing the half saturation value K_{hyd}. μ_{max} is a metabolic parameter depending on the involved biomass and substrates. K_{hyd} is a lumped parameter which mainly considers physical constraints like diffusion resistance and active surface which both get impacted by THP (viscosity reduction and surface generation). Therefore, K_{hyd} is proposed to be reduced and calibrated to available data.

Energy model

All the elements of the energy model are developed in the open environment of the SUMO© simulator platform, where it is coupled with the already established process model (Dynamita 2018). The energy-model describes energy transfers between and within process units and also conservative conversions of one energy-species to the other in order to facilitate coherent balances over the entire system (Wett *et al.* 2016). The considered energy species are heat, electricity, and chemical bound energy. The heat capacity is distinguished between sludge solids and defined substances (water, gas, etc.). The heat capacities of defined substances are obtained from the National Institute of Standards and Technology (NIST) database (NIST 2017). The heat capacity of sludge dry solids is assumed to be 1,700 J/kg.K (Zhao *et al.* 2014). The heat loss P_{loss} (Equation (1)) of each temperature vessel is modelled with a combined factor for surface (A) and thermal transmittance

(k_H). The calibration parameter (k_HA in [kW/K]) is comparable to the k_LA factor known from aeration systems (Tchobanoglous & Burton 1991) and was matched to performance data and the average temperature difference (ΔT) between the corresponding vessel and its ambience.

$$P_{loss} = k_HA \cdot \Delta T \tag{2}$$

The model is set up for Blue Plains THP-specifications and accounts for different temperature levels, evaporation and apparatus specifications like turbine performance, heat supply capacities and efficiencies, as well as pressure restrictions of vessels. Buffering volumes (gas and sludge storage) are neglected. Heat of condensed phases with temperatures higher than flash temperature and steam heat (above atmospheric pressure) is referred to as HT-heat while heat at temperatures between 0 °C and flash temperature is referred to as LT-heat.

The CHP is modelled based on turbine performance data with a nominal net electric efficiency of 30% under full load with an assumed linear efficiency drop of 0.175% per turndown (%) (Solar Turbines 2001). The certain heat loss in the exhaust gas is modelled with an exhaust temperature of 386 °C based on performance sheet after heat recovery and an over stoichiometric air to fuel ratio of 110%. Furthermore, a power loss fraction of 5% of the gas energy at nominal power is assumed to account for dispersed heat losses of the whole system through hot surfaces. The duct burner is modelled with a constant thermal efficiency of 90%. An alternative gas engine is simulated with an assumed electric efficiency of 35% and a high temperature heat fraction of 50% of usable heat. All other device parameters are assumed to be equal to the gas turbine.

The dynamic simulation mimics the system behaviour of a period with a dynamic heat demand (caused by variable sludge throughputs). Due to the lack of dynamic data, the dynamic sludge amount to be treated is modelled by auxiliary data. First, the monitored yearly average sludge production is overlapped with a daily dynamic pattern which is obtained from the power demand of centrifuges in that period. Then, the daily dynamic data are overlapped with an hourly dynamic pattern based on a standard dynamic plant influent (Langergraber *et al.* 2008) with relative extremes of 77% and 117% of the daily average, respectively. The four trains are modelled with a maximum capacity of 500 t/d of wet sludge each. The trains are fed consecutively depending on the instantaneous demand.

Steam production is a continuous process determined by the gas production and operation of the turbines, HRSGs and duct burners, while THP is a batch process with temporary steam demands only during the heating phase of 15 min. To overcome this discontinuity, each THP train is designed with six parallel batch reactors. The heating phase is shifted in time by approximately 15 min. Thus, the process becomes quasi-continuous because the total cycle time is 90 min (filling, heating, holding, depressurizing, discharge). The quasi-continuous demand depends upon the THP system being operated at maximum sludge throughput rates and ideal time shifts. Lower throughput rates, maintenance, or mismatched process steps cause imbalances with periods of temporary low or high steam demand. A train in operation is calling for a constant steam demand as soon as it goes in service with a desired steam temperature of 180 °C. The model THP calls for a certain amount of steam (here 90 t/d) as soon as it goes in service to avoid steam shortages at any time. This scenario was then described by a coupled energy and process model to analyse the process, optimization potentials and limitations in combination with energy issues.

RESULTS AND DISCUSSION

Process model – effects of THP on AD

The full disintegration leads to fully sterilized substrate which means that no biomass is added to the digesters. Therefore, biomass within the digester can only be maintained by biomass growth. A different equilibrium and food to microorganism ratio (F/M) within the digester must be expected because of a different feed fractionation. A shift in X_B/X_{BIO} accelerates the hydrolysis rate without changing model parameters (see Figure 2). Low loaded digesters almost completely remove X_B resulting in very low X_B/X_{BIO} ratios. Higher X_B/X_{BIO} will therefore lead to intensified hydrolysis and fermentation (under equal COD-loads) resulting in improved degradation. A reduced K_{hyd} value will also lead to higher hydrolysis rates and an earlier rate peak meaning that less substrate is needed to reach highest hydrolysis rates. High solids digestion, which is enabled by low viscosity sludges, also leads to faster hydrolysis rates. All effects combined lead to significantly increased process rates in hydrolysis limited AD. Therefore, the THP process model is suitable to mimic the reported effects where improved AD is seen with THP sludges (Zhang *et al.* 2017).

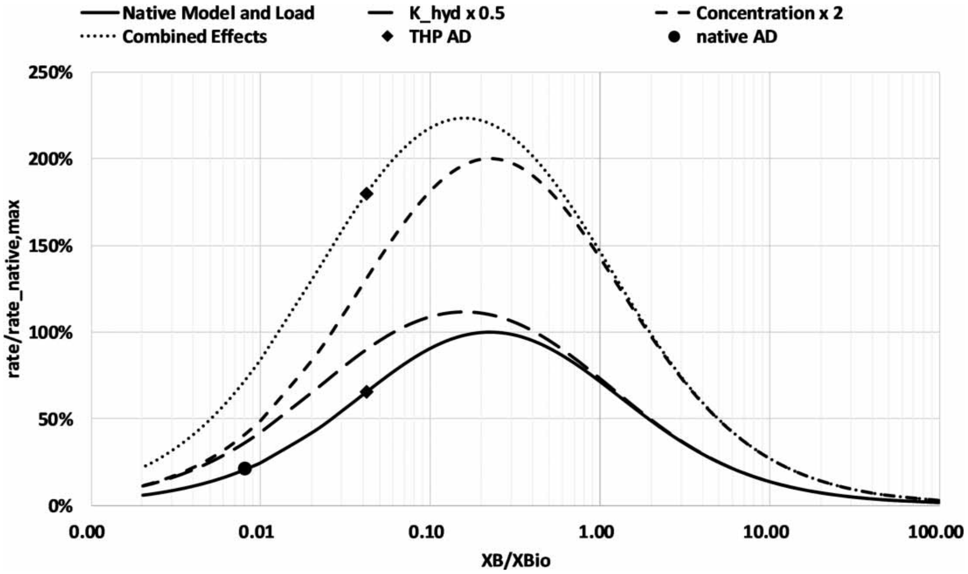

Figure 2 | Hydrolysis rates depending on the ratio X_B/X_{Bio} in the digester. Process rates are normalized to the maximum observed rate at conventional digestion (without THP).

Energy model

The current situation at Blue Plains is described by following steady-state energy balance (Figure 3). The figure depicts how energy is converted within the system and where energy is generated from calorific energy, then recycled and wasted. The heat out of sludge cooling (CHEX) prior to digestion is currently not used. The exhaust heat out of the CHP is not completely needed for steam generation. Surpluses are also wasted. The steam wastes result from the underloaded reactors where steam is demanded, but not fully consumed. The heat loss of hot surfaces of each unit is relatively small compared to other energy streams.

Dynamic effects

Under dynamic situations, steam wastage can be examined in detail (see Figure 4). On many days, three trains (30.5 GJ/h with 10.17 GJ/h for each train) would be sufficient to process the sludge. The relative workload in regard to the capacity of each train determines the amount of steam wastage.

The actual heat demand for steam consumption (Figure 5) matches the simulation results from above. The steam production, however, is larger than the simulation predicts. This can be attributed to temporary larger steam reserves in reality than assumed in the model supplemented

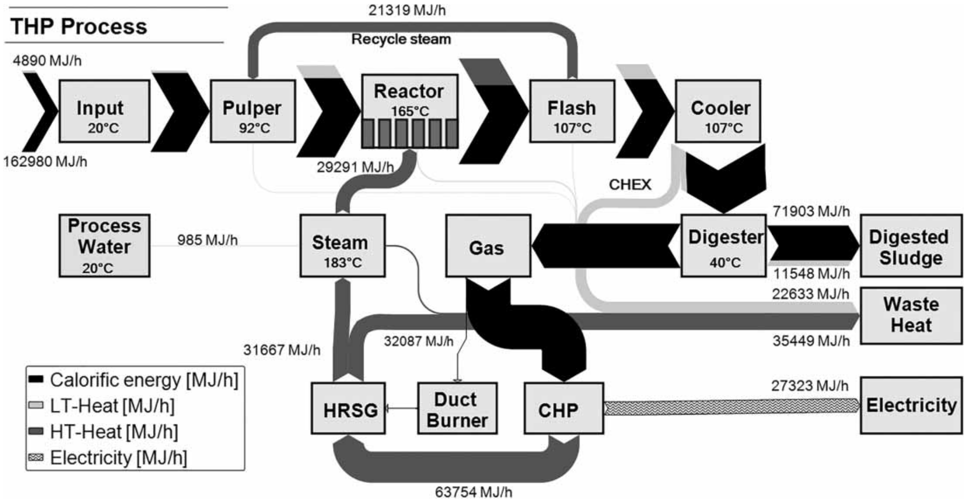

Figure 3 | Sankey-diagram of the steady state energy balance of the sludge system for Blue Plains. LT: low temperature heat; HT: high temperature heat; calorific energy: chemically stored energy (as COD), CHEX: digester cooler heat exchange, HRSG: heat recovery steam generator.

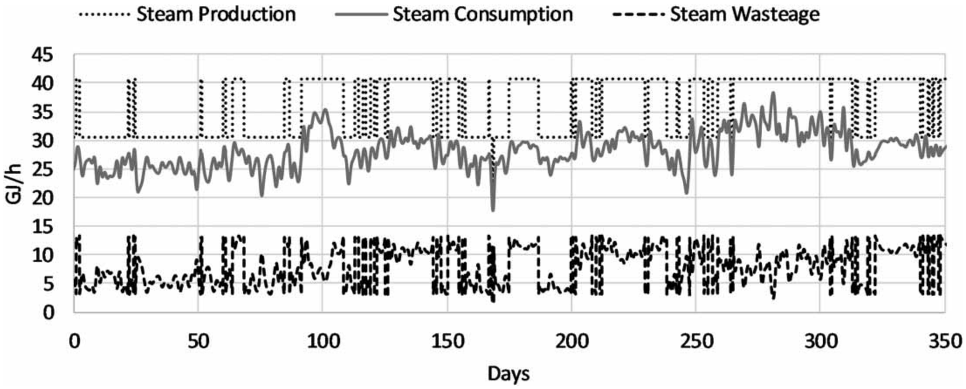

Figure 4 | Simulated steam demand, steam production and steam wastage.

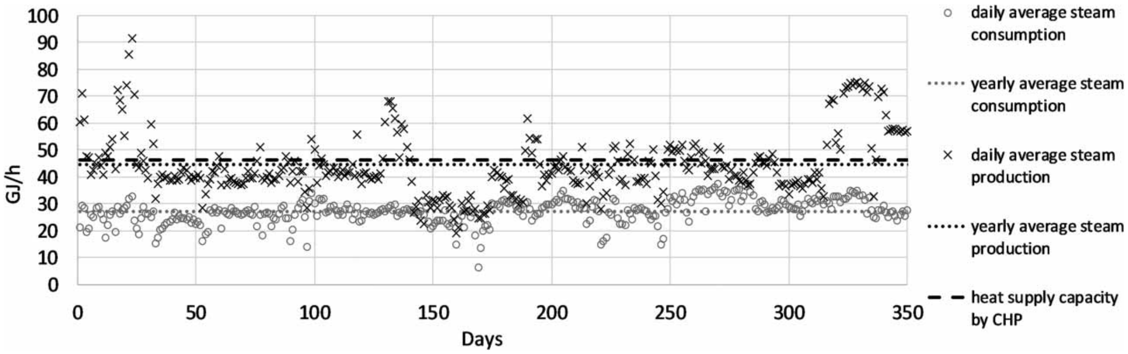

Figure 5 | Steam production and steam consumption at the THP-system Blue Plains. Supply capacity is limited by the average gas production. Steam production above CHP capacity necessitates duct burner operation.

by additional steam demands for auxiliary processes like intermediate reactor venting and other steam processes which are not considered here.

Figure 5 also shows that the heat supply capacity by CHP (limited by average gas production) is still enough to serve both steam consumption and steam production, including steam wastage on a yearly average. However, short term demand exceeds the heat supply capacity by CHP and necessitates the use of the duct burners which trades off potential electric energy gains from CHPs to overcome temporary heat shortages.

The large reserves in steam production are attributed to mismatched cycles of the six batches. Figure 6 illustrates the actual steam calls for every batch of one train for a period of two cycles. It can be seen, that the steam calls are not ideally shifted in time and sometimes batches do not operate properly. This leads to periods of temporary low and high steam demands which necessitates a larger steam production value

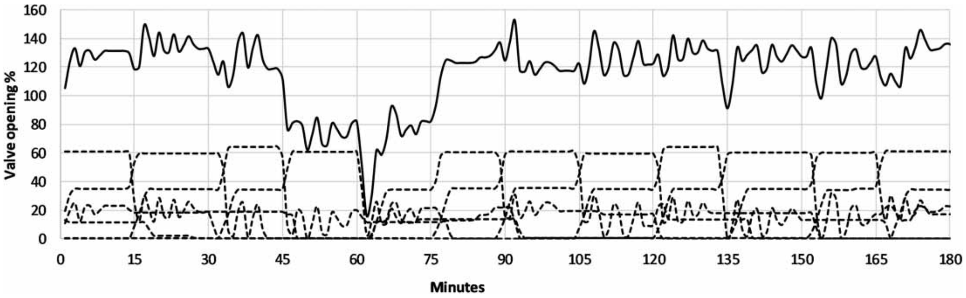

Figure 6 | Train 2 steam valve position of single batches (dashed lines) and summation of all valve positions (solid line).

to serve peak demands. Ideal shifting (i.e. even steam demand) would lead to an even value for the summation curve throughout.

When gas production is too low to serve the instantaneous steam demand, an increasing fraction of gas is fed to the duct burners to avoid heat shortages within the steam production (see model results Figure 7). Therefore, this gas fraction cannot be used for electricity production. The simulation computes a missing gas fraction of 7% which was used by the duct burners instead of CHP.

The total electric energy difference compared to steady state was found to be 30% which is a result of gas trade-offs and efficiency losses in part load operation.

The actual full plant electric energy trade-off for the examined period was found to be 29% which agrees with the model results.

Reduced times of duct burner operation can be achieved by two means. Either total steam production is reduced by steam saving measures like heat recovery or more concentrated sludges, or by matched dynamics of heat supply on demand. A smart heat shift could be achieved by a more stringent control of the THP process or a turbine control matching sludge quantity. Mismatched supply and demand can also be buffered by gas storage, sludge storage or steam storage vessels.

Model aided assessment of energy efficiency improvements

As a first optimization attempt, the excessive heat from CHEX was used to preheat the input sludge (Figure 8). The CHEX heat is abundant at a level of 107 °C which makes it suitable to heat the cold sludge up to 90 °C. However, there is a large recycle stream of steam that results from the flash process which is determined by the difference of reactor and flash temperature. Preheated input sludge would cause a surplus in recycle steam since it cannot condensate in the pulper which is controlled at ambient

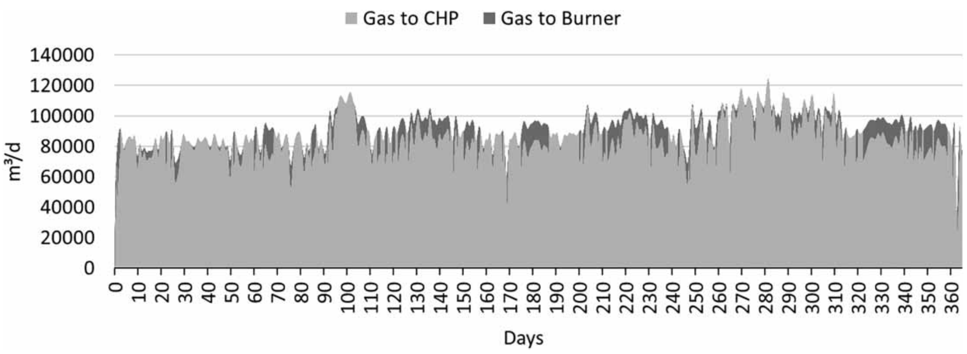

Figure 7 | Modelled gas production and usage within each gas consumption unit to serve the HT-heat energy demand.

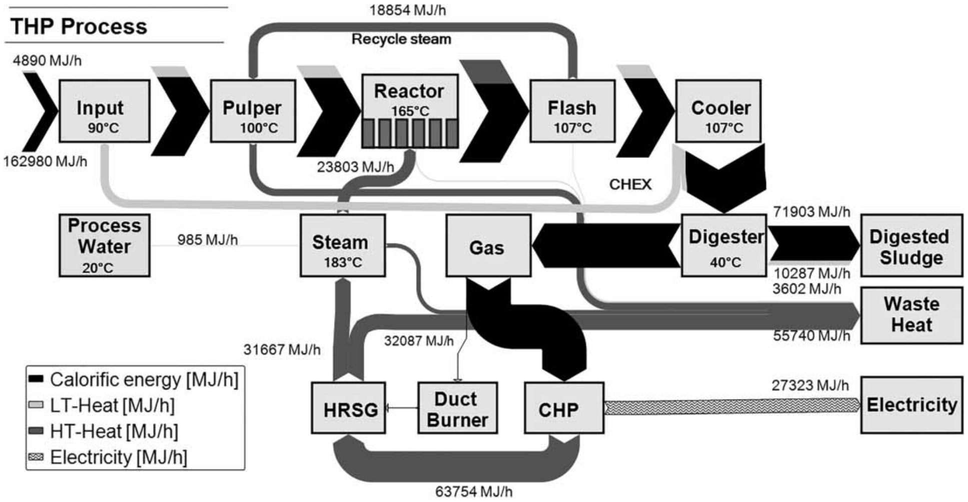

Figure 8 | Steady state energy-balance of the sludge system for Blue Plains with full CHEX heat recovery results in recycle steam wastage.

pressure (<100 °C). Thus, the space for additional heat within the pulper is rather small and recovery of heat from the CHEX for input sludge pre-heating results in recycle steam wastage. Still, the live steam demand can be decreased considerably. The recycled steam condensate increases the total sludge mass which needs to be heated up to reactor temperature afterwards. The live steam heat for this mass can be saved when 'dry' heat from CHEX was used for sludge preheating. As a result, the constant steam supply per train can be reduced from 90 to 70 t/d. From a steady state view, the steam savings do not come into effect since no steam shortage can be observed with this approach since average steam heat demand for both scenarios is lower than the average available HT-heat by CHP. Therefore, the saved heat from the optimization would also be wasted, here within the CHP exhaust.

From a dynamic point of view, the heat recovery leads to increased electricity production due to almost completely reduced periods of HT-heat shortages (as depicted by Figure 7) with almost no gas (<1%) being fed to the duct burners. This results in an increased electricity production of 9.4 MWh/d.

In the second optimization run, the potential of gas engines instead of turbines is tested additionally to sludge preheating by CHEX-heat which results in an electric energy production of 4.7 MWh/d below the baseline scenario. The more efficient electricity production is here overcompensated by HT-heat shortages which necessitated extensive duct burner operation to supplement the heat. Therefore, the combination of gas engines and duct burners cannot outcompete the gas turbines.

CONCLUSION

The combination of energy and process models in THP-systems allows to address interfering effects of energy and process. In the case of Blue Plains, static energy balances help to understand the process, but optimizations can only be assessed by dynamic simulations. A demand-oriented steam production control seems to be the major step towards energy efficiency in the THP process on Blue Plains. Although the heat supply by CHP is enough to serve steam production (including steam wastage) on a yearly average, short term effects like mismatched batches and temporary gas shortage affects the total energy balance considerably.

Reduced steam demand leads to fewer events of gas shortage and could therefore effectively increase electricity production. Timely matched sludge processing and steam production, as well as steam production and gas production, were found to be beneficial to increase energy efficiency.

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