Research Paper

Introducing hydrothermal carbonization to sewage sludge treatment systems—a way of improving energy recovery and economic performance?

Marzieh Bagheri [*], Elisabeth Wetterlund

Division of Energy Science, Luleå University of Technology, 97187 Luleå, Sweden

ARTICLE INFO

ABSTRACT

Hydrothermal carbonization (HTC) can mitigate the disposal costs of sewage sludge in a wastewater treatment plant. This study analyzes the impact of integrating HTC with anaerobic digestion (AD) and combustion from a combined energy and economic performance perspective. Net energy balance and investment opportunity are investigated for a number of technical scenarios considering i) different combinations of the technologies: AD + HTC, AD + thermal dryer + combustion, and AD + HTC + combustion, ii) different options for HTC process water treatment: wet oxidation (WO) + AD, and direct return to AD, and iii) different products: heat-only, heat and electricity, hydrochar, and phosphorus.

The results show trade-offs between investment cost, self-supplement of heat, and output electricity when WO is used. In AD + HTC, net heat output decreases compared to the reference plant, but avoided disposal costs and hydrochar revenue result in profitable investment when the process water is directly returned to the AD. Although HTC has a lower heat demand than the thermal dryer, replacing the thermal dryer with HTC is only possible when AD, HTC, and combustion are connected, or when WO covers HTC's heat demand. HTC may impair the electricity production because of the necessity for a high-temperature heat source, whereas the thermal dryer can utilize a low-temperature heat source. In conclusion, energy advantages of HTC in AD + HTC + combustion are insufficient to provide a promising investment opportunity due to high investment costs of HTC. The investment opportunity improves by co-combustion of hydrochar and external sludge.

1. Introduction

In sustainable sewage sludge management, pollution prevention, resource recovery, and cost efficiency must be simultaneously addressed. High phosphorus (P) concentration and centralized access through wastewater treatment plants (WWTPs) make sewage sludge a promising alternative to limited and unevenly distributed phosphate rock as fertilizer feedstock (Jupp et al., 2021). However, while sewage sludge contains useful resources, it is legally classified as a waste and often perceived as a burden to the holder (Oladejo et al., 2019). Thermal treatment technologies are being introduced as promising solutions in sewage sludge management, to recover valuable resources without spreading contaminants (Gao et al., 2020). However, energy-intensive drying is required before sewage sludge can undergo thermochemical conversion (Czerwińska et al., 2022; Mayer et al., 2021). The high moisture content of sewage sludge causes a low heating value that impedes auto-thermal combustion, decreases the energy density of produced bio-oil in pyrolysis, stimulates tar generation in gasification, and

has the potential to produce erosive sulphuric compounds (Oladejo et al., 2019).

Hydrothermal carbonization (HTC) allows the direct conversion of wet sewage sludge to a char slurry through treatment at high temperature (180–250 °C) and pressure (10–50 bar) (Escala et al., 2013; Gerner et al., 2021). HTC reduces the volume, improves sludge dewaterability, and densifies the energy content (Merzari et al., 2020; Zhao et al., 2014). Dewatering of the HTC slurry can provide hydrochar with up to 70 % solid content (Merzari et al., 2019) and leave behind process water (PW) containing easily-biodegradable organic matter (Aragón-Briceño et al., 2021; Marin-Batista et al., 2020). It has been reported that implementing HTC, followed by solid-water separation, reduces 61 % of heat and 65 % of the electricity demand of dewatering, compared to thermal drying (Wang et al., 2019a).

From a nutrient recovery perspective, Marin-Batista et al. (2020) showed that organic P in digested sewage sludge changes to inorganic P during HTC, which gives the chance to recover the majority of the P content from the hydrochar through acid leaching followed by

precipitation (by adding CaO). Further, HTC in combination with anaerobic digestion (AD) of the PW has been shown to increase the biogas production. Hämäläinen et al. not only demonstrated an increase in biogas production (182–206 mL-CH$_4$/g-COD (chemical oxygen demand)) through PW treatment by AD, but they also showed that the heavy metal (HM) levels of the hydrochar were below the limits for fertilizer, with no detectable pharmaceutical components remaining (Hämäläinen et al., 2021). Aragón-Briceño et al.(2021) investigated the addition of HTC and AD to an existing WWTP for different treatment scenarios of primary sludge, secondary sludge, and mixed sludge. They showed that in addition to reaching total solids and COD reduction of up to 68 and 66 %, respectively, 0.02–0.06 kg struvite per tonne of sludge treated can be produced. Further, the inclusion of produced hydrochar enhances the overall energy recovery of WWTP by up to ten times when compared with biogas production only (Aragón-Briceño et al., 2021). Similar conclusions were drawn by Marin-Batista et al. (2020), who demonstrated a total potential energy recovery of 95 % when producing hydrochar from sewage sludge and biogas from the PW. Since HTC shows a high potential for surmounting one of the important challenges of sewage sludge treatment, i.e., reducing moisture content (Aragón-Briceño et al., 2021; Czerwińska et al., 2022), the evaluation of introducing HTC in existing wastewater treatment and combustion plants is imperative.

Sewage sludge treatment and disposal costs in a WWTP account for 50 % of operational costs (Rulkens, 2008). Wastewater and sewage sludge management projects are non-profitable without external financial support (Medina-Martos et al., 2020). Improving energy recovery should thus be a priority for sewage sludge treatments as it stimulates the energy self-sufficiency in WWTPs (Gu et al., 2017). Following this, this paper investigates the potential to improve the energy and P recovery of existing integrated sewage sludge treatment facilities, through introduction of HTC.

The economic feasibility of integrated systems incorporating HTC, versus improvement in energy and P recovery, has previously been highlighted by only a few studies in a relatively limited way. As mentioned above, Aragón-Briceño et al. (2021) evaluated the economic benefits of HTC based on potential revenues of heat, power, hydrochar, and struvite in an integrated system, without, however, considering the impact of investment cost. Medina-Martos et al. (2020) focused only on the integration of AD and HTC, which is able to improve the energy recovery by 14 % compared to benchmark AD for sewage sludge, while the investment cost increases by 37 %. Zhao et al. (2014) also reported a positive economic perspective for replacing a thermal dryer with HTC in a combustion process, with the objective to reduce external energy resources for the thermal dryer.

To the best of the authors' knowledge, no attempt has yet been made to conduct a techno-economic analysis of the entire treatment system for sewage sludge, including HTC integrated with AD and combustion, from treatment to end products and disposal, while accounting for all associated integration costs. Therefore, this paper investigates the economic feasibility of adding HTC in existing WWTPs with two different sludge treatment processes as follows:

(1) When sludge in the WWTP is treated only by AD and dewatering and the plant needs to pay for the sludge disposal, adding HTC turns sludge into hydrochar that can be sold to a potential market as a final product.
(2) When WWTP includes an existing combustion process situated at the WWTP plant site, adding HTC as pre-treatment before the combustion process becomes an alternative for a thermal dryer.

Integration of WWTPs and combustion plants provides a great opportunity to develop an energy-self-sustained sewage sludge treatment system, while the integration often suffers from site-related conditions, such as size and distance. Conversely, combustion plants require expensive infrastructure that is more economically feasible on a large

scale. This paper addresses the mentioned opportunities and challenges.

The overall aim is to analyze the effects on the entire sewage sludge treatment, from additional biogas production, PW treatment, P recovery, disposal cost, and combustion plant performance. Two research questions are formulated:

1. Is introducing HTC to an existing sewage sludge treatment system technically and economically feasible?
2. Can adding HTC to a WWTP improve the energy performance of the entire sewage sludge treatment and enable P recovery?

The research questions are addressed by developing a techno-economic analysis of a number of technology scenarios. As it is important to provide evidence that an integrated treatment system enables sustainable sewage sludge management concerning resource recovery at a low cost, the results offer comparisons of the net energy balance and economic performance of HTC as part of a comprehensive sewage sludge treatment strategy.

2. Methods and input data

This paper evaluates the energy and P recovery as well as economic viability of introducing HTC into sewage sludge treatment systems, compared to the corresponding reference scenario without HTC, under two sets of technical scenarios:

S1. HTC is added to an existing WWTP with AD. Without HTC, the sewage sludge undergoes AD, after which is mechanically dewatered and transported to an external centralized waste processing plant. When HTC is added to the WWTP, the sludge is converted to hydrochar and can be sold in a potential market, thereby avoiding disposal costs in the form of transportation and gate fee to the centralized waste processing plant. In this scenario, HTC investment costs are thus evaluated in relation to saved disposal costs and revenues for new streams, with the WWTP with AD as reference.

S2. HTC is added to an existing integrated WWTP that includes both AD and combustion for either heat-only production, or combined heat and power (CHP). Here, the existing thermal belt dryer, the pre-treatment of combustion, is assumed to need replacement. Therefore, investment in HTC is here compared to investment in a new thermal dryer. Replacing the thermal dryer with HTC in the S2 scenarios reduces the total inlet fuel volume to the boiler compared to in the reference system. The boiler thus works with free capacity, which is economically unfavorable. This could provide an opportunity for the plant to receive external sludge (ES) from other WWTPs and obtain a gate fee, while simultaneously producing more heat and electricity.

Mass and energy balance analysis is performed for each scenario (shown in detail in Fig. 1). The balances are also used as the basis for the economic evaluation. The following sections provide detailed information on the investigated technologies and scenarios (sections 2.1 and 2.2), the process modeling (section 2.3), and the economic evaluation (section 2.4).

2.1. Technology scenarios

2.1.1. HTC technologies

In HTC, the majority of the carbon (more than 60 %) ends up in the solid phase as hydrochar, with less than 40 % moved into the liquid-phase and about 2–5 % lost in the gas-phase (Wang et al., 2019a). Many studies have considered integrating AD and HTC to improve the biodegradability of organic matter (Aragón-Briceño et al., 2017, 2021; Hämäläinen et al., 2021; Marin-Batista et al., 2020; Medina-Martos et al., 2020; Wirth et al., 2015) and, thereby, the biogas production, by recirculating PW into AD (Medina-Martos et al., 2020; Merzari et al., 2019). Feedstock, process configuration and conditions affect the biogas production when HTC and AD are integrated. Aragón-Briceño et al. (2017) showed that one step thermal pre-treatment (120–170 °C for
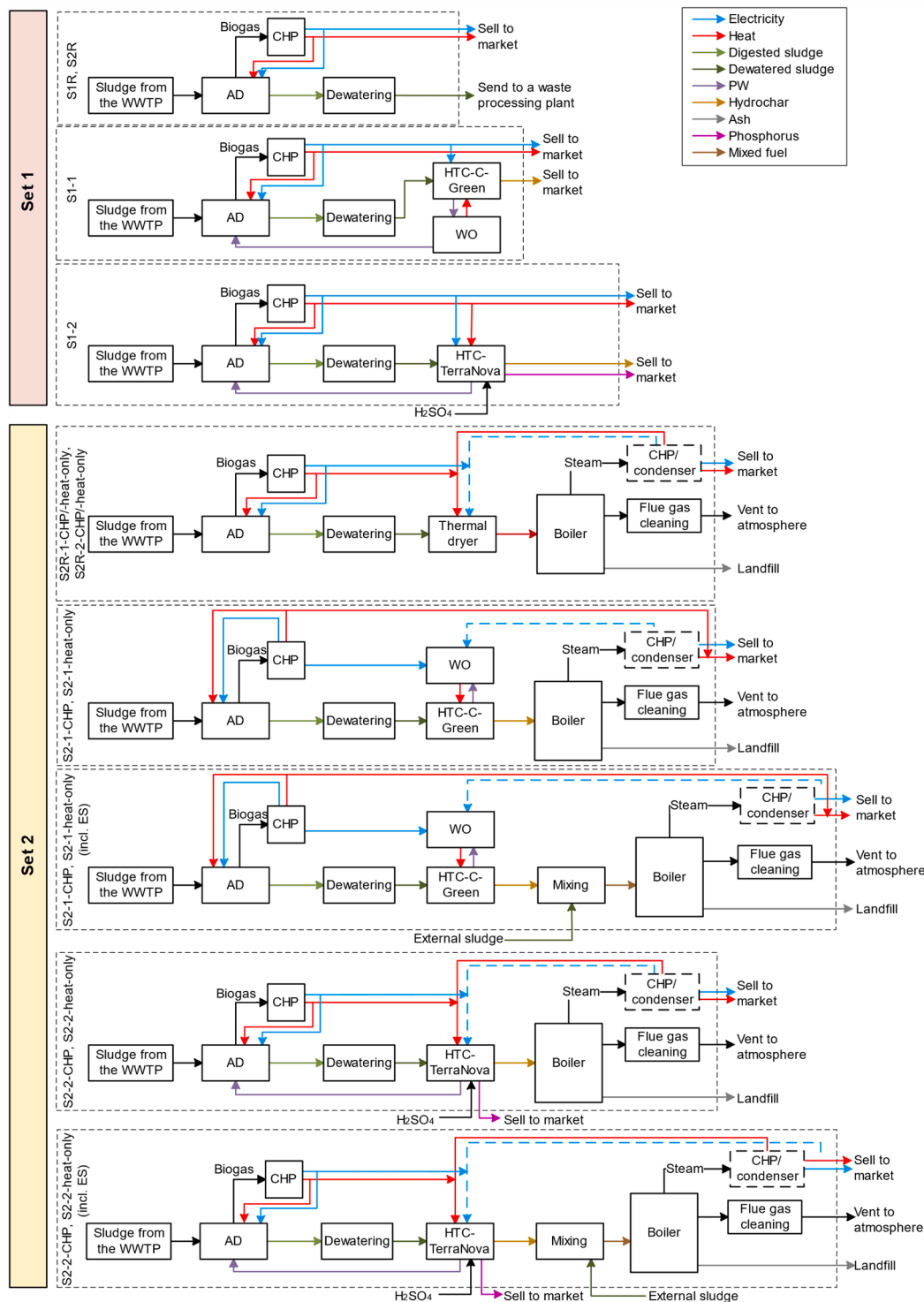
Fig. 1. Schematic of technical scenarios, where HTC is added to an existing WWTP facility scenario. "S1" and "S2" represent set 1 and set 2 of scenarios. "R" indicates reference scenarios without HTC. Scenarios utilizing the HTC-C-Green and HTC-TerraNova technologies, are respectively indicated by "-1" and "-2" at S1 and "-1-" and "-2-" at S2. In the second set of scenarios, the dashed CHP after boiler indicates two forms of steam utilization; i) combined heat and electricity production, or ii) heat-only, respectively. Dashed lines indicate optional flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

30–60 min) can improve the biogas production in AD by 22–43 %, with a methane content increase of 40–70 %, while Qiao et al. (2011) reported a methane yield improvement of 65.8 % when PW from HTC (170 °C at 1 h) was recirculated into the AD. Similarly, Ferrentino et al. (2020) demonstrated that recirculating PW and hydrochar into the AD along with primary and secondary sludge doubled the biomethane yield.

PW can also be treated by wet oxidation (WO) (Shen, 2020) which can reduce the chemical oxygen demand (COD) of PW by 50–70 % (Silva Thomsen et al., 2022; Weiner et al., 2018). Organic matters in WO are oxidized by air or O_2 to CO_2 and water at a high temperature

(100–320 °C) and pressure (0.5–20 MPa), and the process can be energy self-sustained (Riedel et al., 2015). The HTC and WO are compatible to be combined due to the similar operation conditions (Riedel et al., 2015). We here include both AD and WO in the studied technology scenarios. Given that AD is commonly used in WWTPs in Europe, adding HTC to a WWTP excludes additional investment for PW treatment in many existing plants as they are already equipped with AD. On the other hand, the heat released from WO can provide energy for the HTC, thus replacing the demand for external fuel.

Two different HTC commercialized technologies are considered in

Table 1

Detailed scenario description and process conditions.

Name of scenario	Description
S1R	The dewatered sludge (25 % DS) is hauled by trucks to a centralized waste processing plant within the travel distance of 100 km, as suggested by (Mayer et al., 2021; Seiple et al., 2017). Therefore, the WWTP pays a gate fee to the waste processing plant that receives the sludge. Biogas produced via AD is utilized in a CHP process to cover the AD's energy demand; with excess heat and electricity assumed to be sold at market prices. Sludge characteristics is taken from data provided by C-Green.
S2R	Same as S1R except the sludge characteristics, which are here provided by TerraNova.
S1-1	After AD, the dewatered sludge (25 % DS) enters the HTC-C-Green reactor. In this process, the reactor's design allows light (assumed 100 % liquid phase) and heavy (slurry) phases to leave the reactor separately. The light phase enters the WO process at 230 °C and 32 bar, where the organic matter in the PW turns to CO_2 and water through oxidation by O_2. The released heat from the oxidation is used for the HTC reactor. Hot and pressurized PW after the WO, and slurry after the HTC, enter flash tanks to produce steam to pre-heat the feedstock. More heat is recovered by mixing a share of the PW after the flash tanks with incoming sludge. The slurry is dewatered by a filter press up to 62 % DS, and the hydrochar is assumed to be directly sellable, without further treatment (Medina-Martos et al., 2020). PW leaving the process is returned to the AD as it contains easily degradable organic matter that improves the biogas production. P mainly remains in the hydrochar and this scenario does not include P recovery.
S1-2	After AD, the dewatered sludge (25 % DS) enters the HTC-TerraNova reactor operated at 200 °C and 20 bar. The slurry output of the HTC enters flash tanks to recover heat for the HTC process, and the hydrochar is separated from the PW through a filter press. The PW is returned to the AD for further treatment, and the semi-dried hydrochar with 65 % DS is assumed to be directly sellable (Medina-Martos et al., 2020). Adding acid to the slurry after the HTC reactor causes P to leach into the liquid phase (PW). By adding Calcium-Silicate-Hydrate granules (CSH) to the filtrate of the filter press, the dissolved P adsorbs at the CSH granules. P-components are recovered by 80 % in the form of hydroxyapatite and struvite, which are assumed to be directly sellable as a substitute for P rock.
S2R-1-CHP	After AD, the dewatered sludge (25 % DS) enters a thermal dryer to increase the heating value to above 4.5 MJ/kg (about 45 % DS), to ensure auto-thermal combustion conditions in the boiler. Produced heat and electricity from the AD-CHP as well as from the steam boiler-CHP are used to cover the heat and electricity demands of AD, thermal dryer, and flue gas cleaning system, and the rest is assumed to be sold at market prices. It is assumed the ash is transported 100 km to a landfill and the WWTP plant pays for the disposal.
S2R-2-CHP	Same as S2R-1-CHP except the sludge characteristics, which are here provided by TerraNova
S2R-1-heat-only	Same as S2R-1-CHP except that the steam produced in the boiler is here used to produce only heat.
S2R-2-heat-only	Same as S2R-1-heat-only except the sludge characteristics, which are here provided by TerraNova
S2-1-CHP	The thermal dryer is replaced with HTC-C-Green (see S1-1 for conditions). The produced hydrochar (62 % DS) replaces the dried sewage sludge as fuel for the boiler. The heat demand of HTC-C-Green is supplied by WO, and produced heat and electricity are used to meet the internal demand of the studied integrated system, with the surplus assumed to be sold at market prices. It is assumed the ash is transported 100 km to a landfill and the WWTP plant pays for the disposal.
S2-1-CHP (incl.ES)	As total ingoing fuel to the boiler in S2-1-CHP is less than the reference case (S2R-1-CHP), the plant can accept external sludge (ES) with 25 % DS from, e.g., a neighboring city and mix this with hydrocar until the mixture has a heating value ≥ 4.5 MJ/kg (about 45 % DS), to ensure auto-thermal combustion conditions in the boiler. As hydrochar has up to 65 % DS and the received wet sludge 25 % DS, a mixture of the two would enter the boiler at 45 % DS when the mass flow of fuel is equal to boiler inlet in the reference case. The mixed fuel enters the steam boiler instead of hydrochar. The plant receives a gate fee to handle the ES. The overall process is otherwise the same as S2-1-CHP.
S2-1-heat-only	Same as S2-1-CHP except that the steam produced in the boiler is here used to produce only heat.
S2-1-heat-only (incl. ES)	Same as S2-1-heat-only except that the plant receives ES and mixes it with hydrochar before entering the boiler, as described for S2-1-CHP (incl. ES)
S2-2-CHP	The thermal dryer is replaced with HTC-TerraNova (see S1-2 for conditions). The produced hydrochar (65 % DS) enters the boiler to produce heat and electricity, from which the ash residue is sent to disposal. Adding acid to the slurry causes P to leach into the liquid phase. P is recovered after the HTC reactor and sold to the market, as explained in S1-2. Produced heat and electricity supply the internal energy demand of both AD and HTC-TerraNova, with the surplus assumed to be sold at market prices.
S2-2-CHP (incl.ES)	Same as S2-2-CHP except that the plant receives ES and mixes it with hydrochar before entering the boiler, as described for S2-1-CHP (incl. ES)
S2-2-heat-only	Same as S2-2-CHP except that the steam produced in the boiler is here used to produce only heat.
S2-2-heat-only (incl. ES)	Same as S2-2-heat-only except that the plant receives ES and mixes it with hydrochar before entering the boiler, as described for S2-1-CHP (incl. ES)

this paper. The technology selection is based on commercial data availability, in order to be able to capture the performance of HTC of sewage sludge in commercial scales, and to include both WO and AD as PW treatment options. OxyPower HTC (here labeled "HTC-C-Green") is a compact design of combined HTC and WO process developed by C-Green in which the required energy for the HTC is supplied by WO of the PW at 230 °C and 32 bar (C-Green, 2022). TerraNova®ultra (here labeled "HTC-TerraNova") is an HTC process developed by the Terra-Nova energy group. The reactor is operated at 180–200 °C and 20–35 bar (Rebling et al., 2020; TerraNova Energy, 2022; TerraNova Energy GmbH, 2022). Both technologies recover heat from products through flash tanks.

Temperature, reaction time, heating rate, and catalyst affect the hydrochar yield and fate of C, nutrients, and HMs during the reaction (Wang et al., 2019a). Higher temperature promotes conversion level, enhances carbon and energy content in hydrochar, and improves dewaterability, while high temperatures cause high organic content in the PW, which is unfavorable (Wang et al., 2019a). Significantly higher heating value of the produced hydrochar has been reported with shorter reaction time (30–60 min) (Wang et al., 2019a). The majority of the C (greater than60 %) and P (as Al, Ca, and Fe salts) are retained in the hydrochar under normal conditions (temperatures around 200 °C) (Escala et al., 2013; Ovsyannikova et al., 2019; Wang et al., 2019a), while 40–70 % of N, 10–15 % P, and 50–70 % of K transfer into the PW

(Wang et al., 2019b). Both technologies included in this paper employ common HTC conditions, which can determine that P in both technologies mainly remains in the hydrochar. Therefore, the opportunity for P recovery, using extraction and precipitation, is similar for both technologies and mainly depends on market demand or legislation.

TerraNova is based in Germany where P recovery from sewage sludge is mandatory (Mayer et al., 2021), so P recovery via acid leaching of the slurry stream downstream the HTC process is part of TerraNova's technology (Rebling et al., 2020; TerraNova Energy GmbH, 2022). Conversely, in the HTC-C-Green process, the P mainly remains in the hydrochar without being recovered. More detailed process descriptions of the HTC processes can be found in the Supplementary material (Appendix A).

Besides the two studied technologies, several pilot and industrial-scale HTC concepts and plants, such as Suncoal, Ingelia, Carborem, and HTC-Cycle, have been developed. While a detailed comparison of these technologies is beyond the scope of this paper, it highlights the potential of various HTC approaches and the possibility of co-processing sewage sludge with other waste streams as alternative solutions in the future of sewage sludge management.

2.1.2. Technical feasibility versus size

There are trade-offs between scale, transportation, technical integration capability, resource recovery, and cost. For WWTPs with sludge

Table 2

HTC and unit process specifications.

HTC, sludge characteristics	Unit	HTC-C-Green S1R-1, S1-1, S2R-1, and S2-1 scenarios		HTC-TerraNova S1R-2, S1-2, S2R-1, S2-2 scenarios	
		Sludge	Hydrochar	Sludge	Hydrochar
Moisture	wt. %	74[a]	38	78[a]	36
Solid content	wt. %	26	62	22	63
C	wt. %	35	33	31	28
H	wt. %	4.8	4	4.6	3.7
N	wt. %	4.8	2.8	4.6	3.2
O	wt. %	20	12	20	10
S	wt. %	1.3	1.3	1.2	3.7
Cl	wt. %	0.050	0.010	0.090	0.050
Ash	wt. %	35	47	38	51
P	mg/kg DS	32,700	47,200	43,725	8,709[b]
LHV	MJ/kg DS	15	15	13	12
Hydrochar yield	% DS	–	63	–	75
PW	**Unit**	**after HTC**	**after WO**	**after HTC**	
COD	g/l	49	15	60	
BOD₇	g/l	17	9	26	
CH$_4$ generation from PW digestion	LCH$_4$/g COD in PW	–	18[c]	14	
Key modeling data					
Unit process	**Feature**	**Unit**	**Amount**	**Reference**	
AD	AD temperature	°C	37	(Medina-Martos et al., 2020)	
	Volatile substance reduction during AD	%	48	(Medina-Martos et al., 2020)	
	CH$_4$ share in biogas	%	65	(Medina-Martos et al., 2020)	
	Heat value of biogas	kWh/m³	10	(Medina-Martos et al., 2020)	
	AD heat demand	kWh/m³ sludge	24.3	(Mayer et al., 2021; Medina-Martos et al., 2020)	
	AD electricity demand	kWh/m³ sludge	1.95	(Mayer et al., 2021; Medina-Martos et al., 2020)	
	Biogas CHP efficiency	% electricity	35	(Mayer et al., 2021; Medina-Martos et al., 2020)	
		% heat	55	(Medina-Martos et al., 2020)	
Belt dryer	Dryer heat demand	kWh/t evaporated water	850	(HUBER technology, 2022)	
	Dryer electricity demand	kWh/t evaporated water	85	(HUBER technology, 2022)	
	Dryer temperature	°C	80–110	(Havukainen et al., 2022)	
Steam boiler	Boiler steam pressure	bar	40	(Neuwahl et al., 2019)	
	Boiler steam temperature	°C	400	(Neuwahl et al., 2019)	
	Excess air	%	30	(Vamvuka et al., 2019)	
	Combustion efficiency	%	98	(Vamvuka et al., 2019)	
	Boiler efficiency	%	85	(Neuwahl et al., 2019)	
	Stack temperature	°C	120	own assumption	

[a] As received.

[b] Calculated.

[c] Wirth et al. (2015).

production lower than 11,000 t dry solids (DS)/a, steam boilers are not technically feasible options. Instead, hot water boilers are standard for smaller plants (HUBER technology, 2021). As hot water boilers are unable to supply heat at the required temperature and pressure for HTC, small WWTPs are excluded in this study. Although common size of fluidized boilers for sewage sludge combustion is 37,000–40,000 t DS/a, plants with as low sludge capacity as 3200 t DS/a (Ruegen, Germany) and as high as 95,000 t DS/a (Lünen, Germany) are in operation in Germany (Schnell et al., 2020). Here we consider a WWTP with a capacity of 11,000 t DS/a, which corresponds to a city with 550,000 inhabitants, assuming a sludge per capita production of 20 kg DS/a.

2.2. Detailed scenario description

Ten technology scenarios that incorporate HTC in the sewage sludge treatment process are outlined and compared with relevant reference cases. The sludge is treated by mesophilic AD at 37 °C with 48 % of the organic matter of the sludge being converted to biogas (Mayer et al., 2021). Afterwards, the digested sludge is dewatered from 4 % to 25 % DS, and the biogas is used in a CHP cycle with a total efficiency of 90 % to produce heat (55 %) and electricity (35 %). Table 1 presents detailed description of the scenarios and conditions, and Fig. 1 shows them in schematics. As two companies have provided HTC technical data based on two different sewage sludges, we use two reference cases corresponding to the sludge characteristics.

2.3. Process modeling

Mass and energy balances from existing installations are calculated based on detailed spreadsheet models of the integrated process configurations shown in Fig. 1. Performed mass and energy balances are used as the underlying factors in estimating the capital and operating cost of the investigate upgrading plants. Table 2 summarizes the process data as applied in the modeling, along with data from the open literature.

Generic HTC models that could be used to provide enough knowledge for full-scale plants, are currently lacking (Rom et al., 2018). The results of integrated experimental and modeling approaches to develop inventory data are limited to experimental design, scale, and feedstock (Akbari et al., 2019; Hedayati Marzbali et al., 2021; Ischia and Fiori, 2021; Medina-Martos et al., 2020). In this study, data for the HTC processes are provided by two companies that have installed HTC on a commercial scale for sewage sludge. A black box model of HTC-TerraNova and a grey box model for HTC-C-Green are applied in this paper based on data and process descriptions provided by two companies (C-Green and TerraNova), as further detailed in the Supplementary material (Appendix A). Table 2 shows the sludge characteristics provided by the companies.

Energy integration is limited to the inside of the system boundary, and surplus produced heat and electricity are valued based on market price, even though they would, in reality, be utilized for internal demand of the WWTP, which in this study has been left outside the system boundary. Additional energy used in the AD due to PW treatment is considered explicitly in the energy balance, while chemicals and energy

Table 3
Equipment purchases cost and data for variable operational costs and prices.

Equipment purchase cost	Unit	Amount	Module/desired capacity (t dewatered sludge/h)
HTC-C-Greena	M€/module	10	2.5/5.7
HTC-TerraNovaa	M€/module	3.2	2.9/5.7
Thermal belt dryer [a]	M€/module	3	2.9/5.7
Variable operational costs			
Chemical prices	**Unit**	**Amount**	**Reference**
$Ca(OH)_2$	€/t	140	(Egle et al., 2016)
H_2SO_4 98 %	€/t	150	(Egle et al., 2016)
NaOH	€/t	303	(Faragò et al., 2021)
Water	€/m3	0.5	(Egle et al., 2016)
O_2 gases	€/kg	0.03	(Young et al., 2021)
Activate Carbon	€/t	1485	(Faragò et al., 2021)
$CaCO_3$	€/t	996	(Egle et al., 2016)
NH3	€/t	300	(Egle et al., 2016)
Energy/product prices			
Heat price	€/kWh	0.06	(Egle et al., 2016)
Electricity price	€/MWh	217	(Nord Pool, 2021)
Hydrochar price [b]	€/t	100	(Lucian and Fiori, 2017; Medina-Martos et al., 2020)
Rocky phosphate [c]	€/t	320	(Bagheri et al., 2022)
Disposal			
Ash disposal [d]	€/t	50	(Eboh et al., 2019)
Fly ash disposal [e]	€/t	120	(Bagheri et al., 2022)
Sludge gate fee [f]	€/t	55	(Eboh et al., 2019)
Transport	€/t km	0.14	(Egle et al., 2016)
Condensate treatment [g]	€/m³	1	(Thomas Brinkmann et al., 2016)

[a]The cost includes all the equipment, piping, electrical, instrument, and engineering costs. These technologies are delivered as an already finished module with everything inside connected, insulated, and ready to operate (C-Green, 2022; TerraNova Energy, 2022). The dryer is the belt type (model BT8) from HUBER technology.

[b]Lucian and Fiori reported the price range of 157–200 €/t for hydrochar production as a competitive price compared to woody biomass, and they also reported the selling price of 150–200 €/t of hydrochar by Ingelia S.L.(Lucian and Fiori, 2017). Reißmann et al. suggested that the hydrochar production cost from sewage sludge should be less than 325 €/t (Reißmann et al., 2020). Medina-Martos et al. considered 103.08 €/t of hydrochar from non-digested sludge (Medina-Martos et al., 2020). In this study, the selected base price of 100 €/t which is close to the given price for sewage sludge-based hydrochar by Medina-Martos et al.

[c]The quality of recovered P is assumed to be similar to phosphate rock.

[d]Cyclone and bottom ash.

[e]It is assumed that 3 % of total ash is taken as fly ash (Neuwahl et al., 2019) known as hazardous waste that is disposed of separately.

[f]The gate fee is the charge that the WWTP pays to the downstream waste processing facility, outside the system boundary.

[g]Due to lacking specific condensate characteristics, a condensate treatment cost of 1 €/m3 is considered based on the reported general cost of the filtration process (Brinkmann et al., 2016).

carrier consumption in the WWTP are excluded from the analysis. The biogas CHP unit is assumed to have a 10 % free capacity that can be used in the scenarios with improved biogas production.

In the first set of scenarios (S1), the biogas CHP provides the internal energy demand. The steam cycle and operating temperature for the thermal dryer in the S2R-1/2-heat-only and S2R-1/2-CHP are chosen so that the condenser can meet the thermal dryer demand. Heat recovery from PW to preheat the sludge for AD is considered in all scenarios that include HTC. The AD, thermal dryer, and combustion processes are modelled according to the approach suggested in (Mayer et al., 2021). The additional biogas production from PW is calculated based on L CH_4 g^{-1} COD yield reported by the open literature.

The flue gas cleaning system for the second set of scenarios (S2) is considered the same both with and without HTC, and for CHP and heat-only (Jurczyk et al., 2016; Schnell et al., 2020). In summary, ammonia or urea is directly injected into the boiler to reduce nitrogen oxides through selective non-catalytic reduction, an electrostatic precipitator removes fly ashes, and a two steps wet scrubber using NaOH or $Ca(OH)_2$ is applied for desulfurization (Kilkovsky et al., 2014; Schnell et al., 2020). Micro and nanofiltration are used for flue gas condensation treatment (Thomas Brinkmann et al., 2016). Other relevant process data is obtained from the open literature (see Table 2).

2.4. Economic evaluation

2.4.1. Evaluation of investment opportunity

Each scenario's economic feasibility is assessed in relation to the corresponding reference scenario, by calculating an annual specific investment margin and annual specific investment cost. This comparative

economic evaluation of the scenarios is performed in two steps.

In the first step, an *annual specific investment margin* (€/t of total dewatered sludge within the system boundary) is calculated by net annual operation income minus variable operation costs (VC) of adding HTC to a given system, divided by inlet tonnes of dewatered sludge per year (equation (1). Operational costs are divided into fixed operational costs (*FC*) at 5 % of total investment costs (*TIC*), and *VC* which include energy, material, and disposal costs (Table 3). Heat, electricity, hydrochar, and P are potential products generating revenues (*R*) for each given scenario. Disposal cost consists of transportation cost to a waste processing plant and gate fee to receive the residue, according to the scenario (dewatered sludge in S1R and ash in S2).

By considering changes between the HTC and reference scenarios in the economic evaluation, effects of introducing HTC to the reference system are consequently highlighted. Thus, a clear connection can be made between investment costs and the changes induced by HTC in the treatment systems.

In the second step, the *annual specific investment cost* (€/t of dewatered sludge) of adding HTC is calculated by equation (2). The TIC of technologies is estimated based on the method explained in (Towler and Sinnott, 2021) (see Supplementary material, Appendix B), and divided by tonnes of dewatered sludge per year, to determine the specific investment costs. The annual specific investment costs are then obtained by multiplying the specific investment costs by an annuity factor (*AF*) (equation (3) of 10 %, based on the interest rate *i* of 8 % and an economic lifetime *n* of 20 years. In S1, TIC is the actual HTC plant cost, while in S2 the cost of a new belt dryer constitutes the reference TIC.

The difference between the annual specific investment margin and the annual specific investment cost shows the viability of investment or
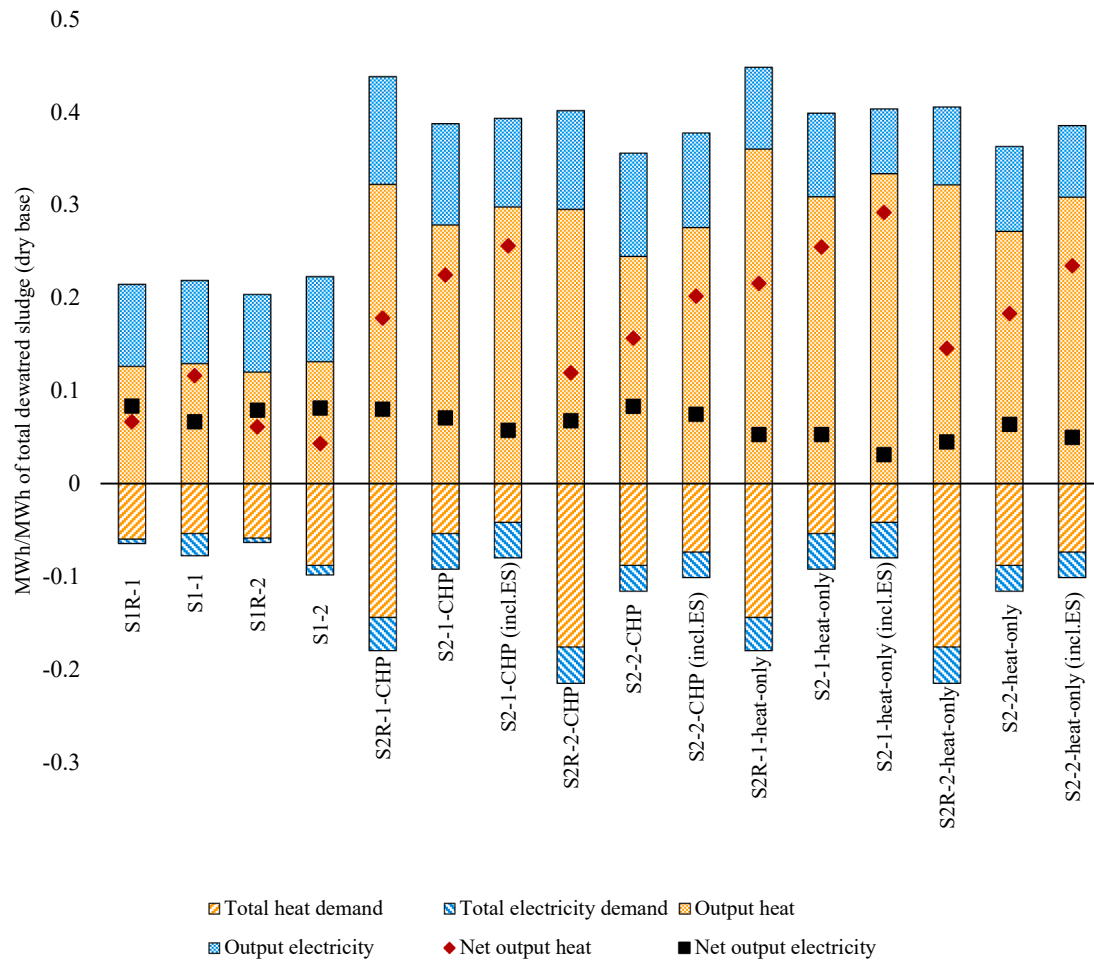
Fig. 2. Breakdown of energy demand and output, and net heat and electricity output of scenarios per inlet energy (MWh/MWh total dewatered sludge inside the system boundary, including external sludge, ES). In "S1" scenarios, HTC is added to a WWTP with an AD facility. In "S2" scenarios, HTC is added to an integrated WWTP that includes both AD and combustion for heat-only or CHP production. "R" indicates reference scenarios without HTC, "-1" scenarios using the HTC-C-Green technology, and "-2" scenarios using the HTC-TerraNova technology. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

investment opportunity in HTC, as the former is based on system changes prompted by the introduction of HTC, and the latter is based on the actual investment cost of HTC. By applying this method, we can determine whether scenarios with HTC improve the economic performance of sewage sludge treatment systems compared to the reference scenarios.

$$\text{Annual specific investment margin} = \frac{(R\text{-}VC)_{scenario} - (R\text{-}VC)_{reference}}{t \text{ of dewatered sludge}} \tag{1}$$

$$\text{Annual specific investment cost} = \frac{(TIC \times AF + FC)_{scenario} - (TIC \times AF + FC)_{reference}}{t \text{ of dewatered sludge}} \tag{2}$$

$$\text{Annuity factor} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

2.4.2. Economic input data

The equipment purchase costs for HTCs and the thermal dryer are obtained from the technology vendors for the year 2022. The sum of the installed cost of technologies (*ISBL*), offsite costs (*OSBL*), design and engineering, and contingency is defined as TIC, as detailed in Appendix B. The HTC has a modular design, so scale-up is done by adding more modules, and the cost of the module contains all the equipment, building, piping, electrical work, instrument, and engineering costs except civil work. The process gas of HTC consists mainly of CO_2; however, it also contains hydrogen sulphide, nitrogen dioxide, nitric oxide and ammonia, which requires further treatment (Hämäläinen et al., 2021).

As the module has all technical requirements, the capital cost of the technologies includes the gas cleaning process, hence energy demand of the gas cleaning is also included in the module energy demand. Although the details of the gas composition are not available, the chemical demand of gas cleaning is included in the data that constitutes

Table 4

Mass and energy balance results applied in the economic analysis for the studied technical scenarios.

Scenarios	AD						Thermal dryer			HTC				
Parameters	Biogas production	Electricity production	Heat production	Electricity demand	Heat demand	Dewatered sludge (25% DS)	Heat demand	Electricity demand	Mass of semi-dried sludge (45% DS)	Hydrochar	Heat demand	Electricity demand	O_2	Water
	m³/h	MWh/h	MWh/h	kWh/h	MWh/h	t/h	MWh/h	kWh/h	t/h	t/h	kWh/h	kWh/h	t/h	t/h
S1R-1	890	2.14	3.06	116	1.45	5.73	0	0	0	0	0	0	0	0
S1-1	908	2.18	3.13	125	1.31	5.73	0	0	0	1.51	0	447	0.49	41.2
S1R-2	725	1.74	2.49	98.4	1.22	5.73	0	0	0	0	0	0	0	0
S1-2	793	1.91	2.73	106	1.09	5.73	0	0	0	1.55	745	103	0	22.9
S2R-1-CHP	890	2.14	3.06	116	1.45	5.73	2.06	206	3.31	0	0	0	0	0
S2-1-CHP	908	2.18	3.13	125	1.31	5.73	0	0	0	1.51	0	447	0.49	41.2
S2-1-CHP (incl.ES)	908	2.18	3.13	125	1.31	7.53	0	0	0	1.51	0	447	0.49	41.2
S2R-2-CHP	725	1.74	2.49	98.4	1.22	5.73	2.44	244	2.86	0	0	0	0	0
S2-2-CHP	793	1.91	2.73	106	1.09	5.73	0	0	0	1.55	745	103	0	22.9
S2-2-CHP (incl.ES)	793	1.91	2.73	106	1.09	7.03	0	0	0	1.55	745	103	0	22.9
S2R-1-only-heat	890	2.14	3.06	116	1.45	5.73	2.06	206	3.31	0	0	0	0	0
S2-1-only-heat	908	2.18	3.13	125	1.31	5.73	0	0	0	1.51	0	447	0.49	41.2
S2-1-heat-only (incl. ES)	908	2.18	3.13	125	1.31	7.53	0	0	0	1.51	0	447	0.49	41.2
S2R-2-only-heat	725	1.74	2.49	98.4	1.22	5.73	2.44	244	2.86	0	0	0	0	0
S2-2-only-heat	793	1.91	2.73	106	1.09	5.73	0	0	0	1.55	745	103	0	22.9
S2-2-heat-only (incl. ES)	793	1.91	2.73	106	1.09	7.03	0	0	0	1.55	745	103	0	22.9

the foundation for the modelling. Table 3 presents the summary of cost and price data used in the economic analysis.

2.4.3. Sensitivity analysis

The total revenue of each scenario is (depending on scenario characteristics) highly dependent on the heat, electricity, hydrochar, and P market prices, as well as the final waste disposal cost (gate fee) of material sent to the waste handling site. Therefore, a sensitivity analysis is performed regarding the impact of market prices and gate fees on the investment opportunity, varying the mentioned variables from −50 % to + 50 %.

3. Results and discussion

3.1. Energy performance

The energy performance of the studied system has several dimensions. While the most critical issue is undisputedly to reduce the sludge's water content and consequently increase its heating value, recirculation of PW from the HTC also has the potential to stimulate biogas production. The results show that recirculating PW to the AD improves biogas production by 9.4 % in the HTC-TerraNova scenarios (S1-2, S2-2-CHP/-heat-only, and S2-2-CHP/-heat-only (incl.ES)), but only 2.0 % in the HTC-C-Green scenarios (S1-1, S2-1-CHP/-heat-only, and S2-1-CHP/-heat-only (incl.ES)) scenarios. The reason is that the organic matter in the PW is oxidized during the WO, which instead provides the heat needed by the HTC reactor.

Moreover, returning PW to the AD in the HTC-C-Green scenarios increases the AD electricity demand by 7.1 %. Therefore, the additional biogas production cannot cover the additional electricity demand of the PW treatment. Conversely, for the HTC-TerraNova scenarios the additional electricity demand of the AD is 8.1 %, while the electricity production improves by 9.4 %. Therefore, additional biogas produced by returning PW to the AD covers HTC-TerraNova's electricity demand.

Fig. 2 shows a graphic representation of the demand and output of heat and electricity for the studied sewage sludge treatment system, for each scenario. Mass and energy balances applied in economic analysis are presented in Table 4, with a detailed balance for each scenario presented in the Supplementary material (Appendix C).

Regarding AD heat demand, recirculating the PW incurs no additional thermal demand, as the PW leaves the HTC at 70 °C. As the AD operates at 37 °C, the PW can be used to pre-heat the inlet sludge to the AD. Therefore, S1-1 has a higher heat output, compared to the respective reference scenario, due to higher biogas production and the possibility to use recirculated PW to pre-heat the sludge. The net electricity output of S1-1 is 20 % lower than that of S1R-1 due to WO demand, and the improvement of biogas production is inadequate to offset the rise in electricity consumption. However, S1-1 has 74 % higher heat output. For S1-2, the effects are the opposite, with 29 % decreased heat output due to HTC demand and 3.2 % increased electricity output, compared to S1R-2.

Replacing the thermal dryer with HTC in the S2 scenarios, without ES, reduces the total heat demand for pre-processing the sewage sludge before combustion and provides a fuel (hydrochar) with higher solid content. The total inlet fuel volume to the boiler is, however, almost halved compared to in the reference system. The boiler thus works with free capacity, which is economically unfavorable. Covering the free capacity of the boiler with ES could increase both energy demand and outputs. S2-1-CHP (incl.ES) outperforms S2-1-CHP in terms of heat and electricity outputs, which increase by 47 % and 4.9 %, respectively. Although the electricity output is still 7.5 % lower than in the S2R-1-CHP, replacing the thermal dryer with HTC and adding ES improves heat and electricity production. Conversely, in S2-2-CHP (incl.ES), the electricity output is 31 % and 6.5 % higher than in S2R-2-CHP and S2-2-CHP, respectively. Although the flue gas cleaning system operates at full capacity, ES covers the demand and improves the electricity output.

Although the energy demand for a thermal dryer is higher than for the HTC process, the thermal dryer can utilize low-temperature heat sources. All HTC scenarios demand high-temperature heat sources (e.g., steam at 240 °C), that can be incompatible with a combustion process. For instance, in S2R-2-CHP, the condenser covers the heat demand of the thermal dryer. In contrast, in S2-2-CHP, if the system was not connected to AD, replacing the thermal dryer with HTC-TerraNova would require steam extraction from the turbine, which would significantly impair the electricity production in the given process. This would make the thermal dryer the better match for the given CHP process, as the process could

HTC		Incineration					Flue gas cleaning system						
H_2SO_4	P recovery	Inlet fuel	Electricity production	Heat production	Electricity demand	Ash	Ca (OH)$_2$	NaOH	CaCO$_3$	Activate carbon	Ammonia	H_2SO_4	Heat recovery
t/h	kg/h	t/h	kWh/h	MWh/h	kWh/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	MWh/h
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	7.96	0	0	0	0.57	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.11	44.9	0	0	0	0	0	0	7.96	0	0	0	0.57	0
0	0	3.31	669	3.04	541	515	7.45	63	2.56	0.9	18	0	1.72
0	0	1.51	464	2.06	357	441	4.92	49.0	1.69	0.59	11.9	0.57	1.57
0	0	3.31	826	3.71	634	703	8.73	80.9	3.0	1.05	21.1	0.57	2.52
0	0	2.86	471	2.17	466	492	6.43	53.7	2.21	0.77	15.5	0	1.48
0.11	44.9	1.55	402	1.80	367	502	5.05	42.8	1.74	0.61	12.2	0.57	0.56
0.11	44.9	2.86	613	2.79	466	710	9.11	66.3	2.71	0.02	19	0.57	1.32
0	0	3.31	0	3.96	541	515	7.45	62.3	2.56	0.90	18	0	1.72
0	0	1.51	0	2.80	357	441	4.92	49.1	1.69	0.59	11.9	0.57	1.57
0	0	3.31	0	4.84	634	703	8.73	80.9	3.00	1.05	21.1	0.57	2.52
0	0	2.86	0	2.72	466	492	6.43	53.7	2.21	0.77	15.5	0	1.48
0.11	44.9	1.55	0	2.36	367	502	5.05	42.8	1.74	0.61	12.2	0.57	0.56
0.11	44.9	2.86	0	3.60	466	710	9.11	66.3	2.71	0.02	19	0.57	1.32

produce more electricity and use low-temperature heat that would otherwise be wasted in case of lacking external heat demand. In S2-2-CHP, the AD-CHP is therefore used to supply the heat for the HTC (high temperature), while heat from the condenser is utilized for the AD heat demand (low temperature). The net heat and electricity output of the given system therefore improves for S2-2-CHP by 31 % and 23 %, respectively, compared to with the thermal dryer. This is due to i) significantly lower heat demand for producing hydrochar (130 kWh/t evaporated water) with lower moisture (from 25 to 64 % DS) content than semi-dried sludge (850 kWh/t evaporated water, from 25 to 45 % DS) and ii) lower electricity demand of the HTC and flue gas cleaning systems, compared to S2R-2-CHP. The decreased electricity demand for the flue gas cleaning, however, is caused by the free capacity of the boiler. It is worth mentioning that a standalone CHP plant (without integration with AD) would, however, be unable to operate with the HTC-TerraNova without impairing the electricity production, unless the plant is a green field project designed according to HTC demands rather than upgrading an existing plant.

Conversely, in S2-1-CHP, WO instead provides the heat demand, which makes it independent of the steam cycle, while instead increasing the process' overall electricity demand. S2-1-CHP has 33 % higher net output heat of the system compared to S2R-1-CHP, but 12 % lower net electricity, due to the factors already discussed above (negligible improvement of biogas production and high electricity demand of HTC-C-Green).

Regarding the heat-only scenarios, S2-1-heat-only has a 18 % higher net output of heat and a 1.7 % lower output of electricity, while in S2-1-heat-only (incl.ES), the heat output increases by 75 % and the electricity output decreases by 22 %, compared to the thermal dryer (S2R-1-heat-only). The effect of WO and flue gas cleaning at full capacity were aggregated in S2-1-heat-only (incl.ES). Conversely, S2-2-heat-only increases the net output of both heat (+26 %) and electricity (+42 %) compared to the reference (S2R-2-heat-only). Again, the increase in net output of electricity is in fact due to the boiler not working at full capacity, and thus having a lower electricity demand. At full boiler capacity, S2-2-heat-only (incl.ES), the heat and electricity output increases by 92 % and 32 % compared to the reference.

In all S2 scenarios, the output heat of the given system increases compared to the reference cases. The output electricity of the system with HTC-C-Green is lower due to the high electricity demand of the WO, while in the system with HTC-TerraNova, the output electricity of the system is improved. When comparing net electricity output differences between CHP and heat-only scenarios, it should be highlighted that the AD-CHP has a significant share in the total electricity production in all scenarios, which is equal in both CHP and heat-only reference cases, and it changes insignificantly in scenarios with HTC. The difference in electricity output between S2-1-CHP and S2-1-heat-only is 37 %, and 30 % between S2-2-CHP and S2-2-heat-only. When ES is added to the boiler, these differences increase to 84 % and 50 %, respectively.

3.2. Economic performance

The energy performance analysis revealed that HTC, in S1, reduces either heat or electricity outputs while, in S2, outperforms the thermal dryer in terms of heat demand. However, the investment cost and external factors such as sludge disposal costs, hydrochar, and energy prices have a large impact on the actual investment opportunity. This section translates those implications into monetary performance. Fig. 3 shows a breakdown of the costs and revenues for the scenarios. The figure also shows the resulting annual specific investment margin, as well as the annual specific investment cost. As described in section 2.4, the difference between the annual specific investment margin and the annual specific investment cost represents the opportunity to invest in HTC. Details of the economic performance, in terms of costs and revenues for each technical scenario, can be found in the Supplementary material (Appendix D).

Notably, only five scenarios (S1-2, S2-2-CHP/(incl.ES), and S2-2-heat-only/(incl.ES)) show a positive investment opportunity for HTC, i.e., a higher annual specific investment margin than annual specific investment cost. Scenario S1-2 exhibits the most prominent investment opportunity where implementing HTC-TerraNova (going from S1R-2 to S1-2) enables an investment cost of up to 96 €/t sludge while the actual investment of the scenario (according to investment cost data provided by the technology supplier) amounts to 42 €/t sludge. The explanation behind this is that adding HTC to WWTP avoids almost 3 M€/a of sludge disposal cost (transportation + gate fee) and instead adds up to 1.2 M€/a of hydrochar revenue, as well as P revenue of 0.11 M€/a, to the system. Under the right circumstances, such as high hydrochar price and gate fee
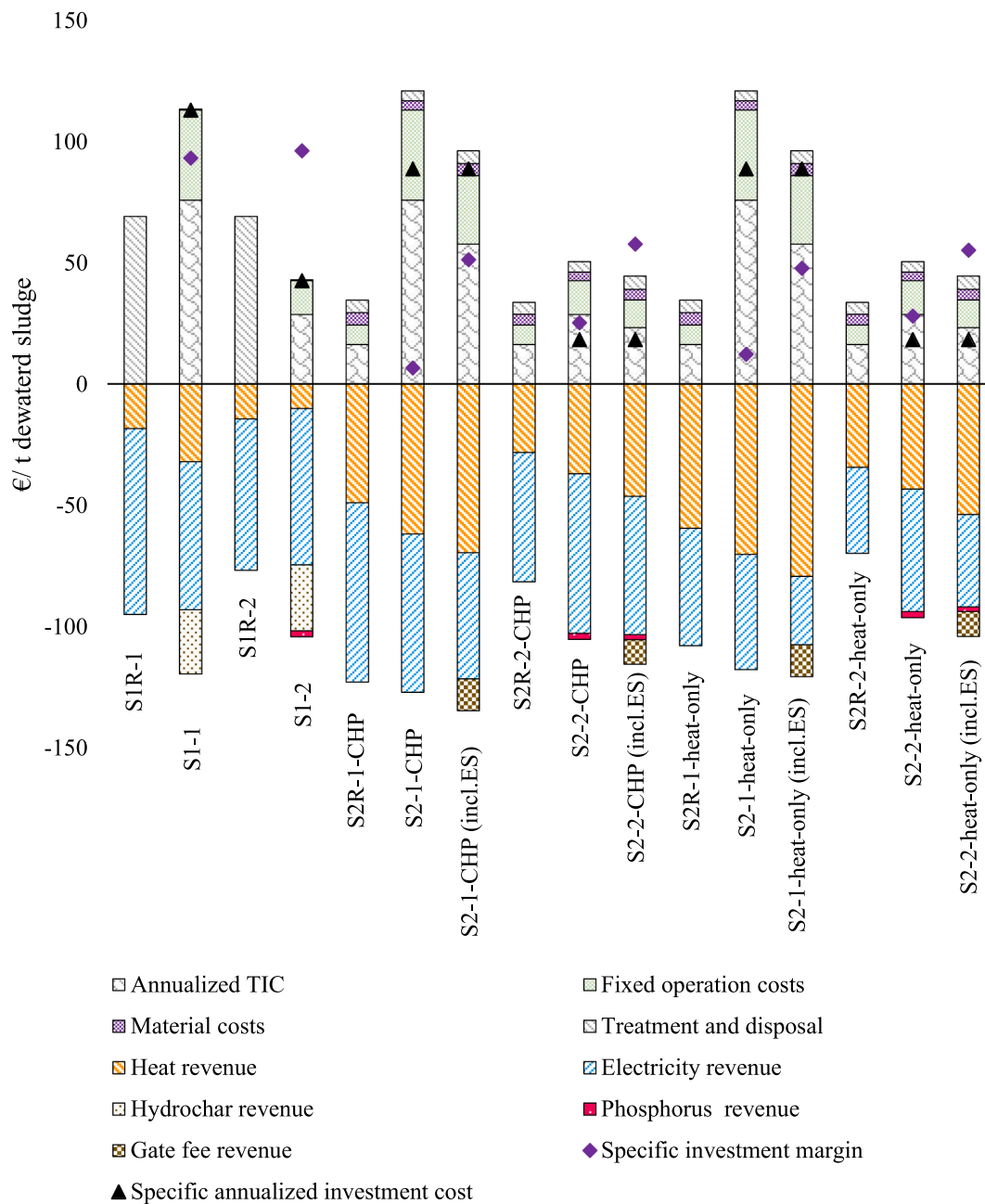
Fig. 3. Breakdown of the treatment cost of sewage sludge, annual specific investment costs, and annual specific investment margins in the studied scenarios. In "S1" scenarios, HTC is added to a WWTP with AD facility. In "S2" scenarios, HTC is added to an integrated WWTP that includes both AD and combustion for heat-only or CHP production. "R" indicates reference scenarios without HTC, "-1" scenarios using the HTC-C-Green technology, and "-2" scenarios using the HTC-TerraNova technology. "(incl.ES)" indicates scenario with co-combustion of hydrochar with external sludge (ES). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cost (see Fig. 4), not only S1-2 but also S1-1 could be an attractive investment, despite having a 2.6 times higher annualized TIC cost than S1-1. External conditions, such as increased transportation costs due to fuel price, or increased landfill costs, would stimulate the investment feasibility of S1-1.

The increase in the net revenue in S2-2-CHP and S2-2-heat-only is respectively 14 % and 20 % compared to the references, with S2-2-heat-only slightly outperforming S2-2-CHP in terms of investment opportunity. Poor sludge quality in these cases and the fact that turning sludge to hydrochar instead of drying it improves the main output (heat) of the S2-2-heat-only could be one reason. On the other end of the spectrum, S2-1-CHP and S2-1-heat-only are economically infeasible due to the high

investment cost of HTC-C-Green, compared to that of the thermal dryer. Further, a higher fixed operational cost due to more complex technology, which, in combination with a reduction in electricity revenue, causes poor economic performance.

Co-combustion of hydrochar with external sludge (ES) to cover the free capacity in the boiler enhances heat and electricity outputs in all S2 scenarios while the plant also receives a gate fee revenue for the ES. Although the specific investment margin in S2-1-CHP (incl.ES) is seven times higher than in S2-1-CHP and thus diminishes the distance between the specific annualized investment cost and the investment margin, the investment opportunity is still negative. Again, the high gate fee and increased energy revenues, in combination with the significantly lower
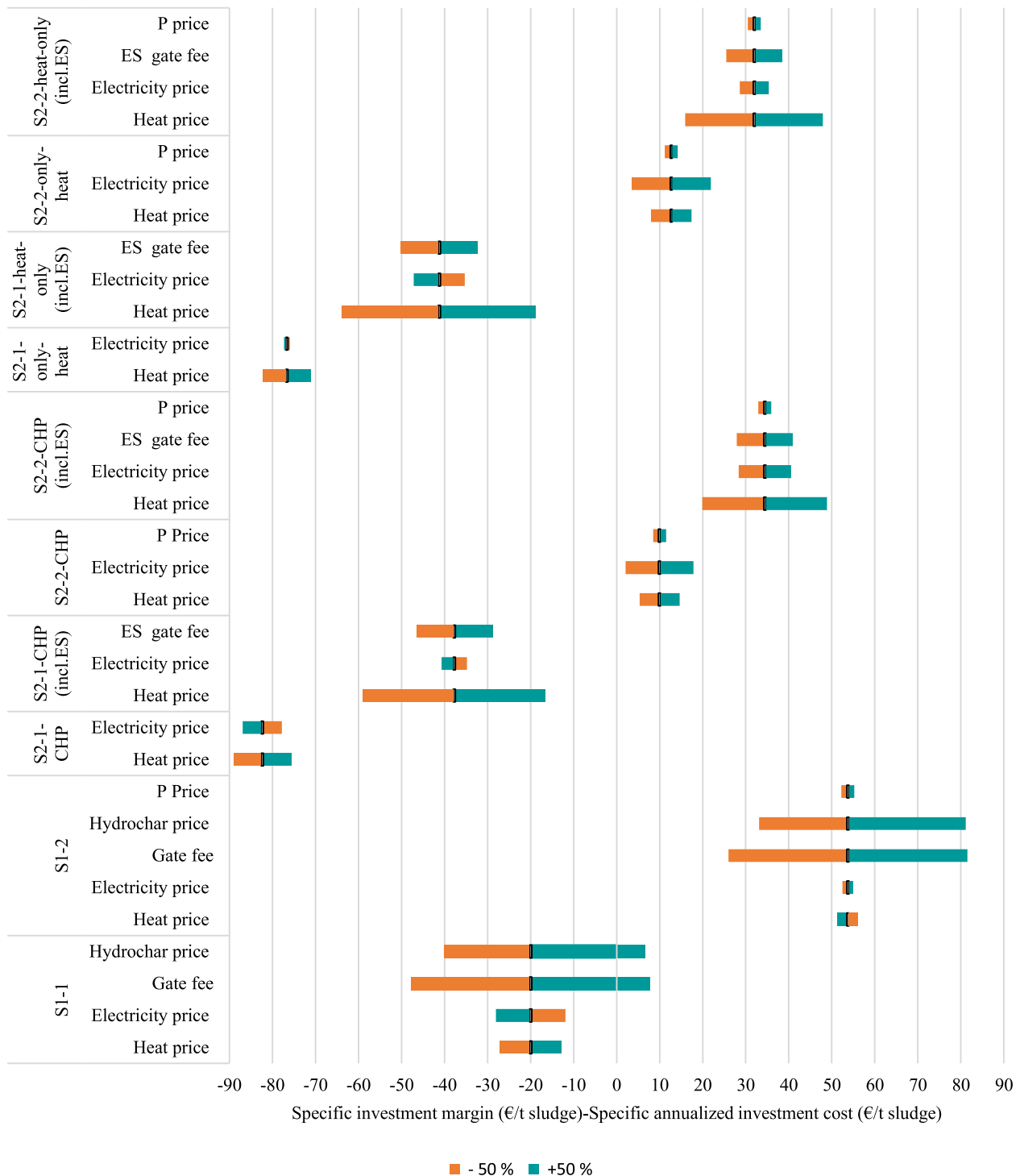
Fig. 4. Sensitivity analysis is performed by measuring the investment opportunity (i.e., the difference between the annual specific investment margin and the annual specific investment cost) when key economic parameters of each scenario are varied between −50 % and +50 %. The reference distance is displayed by black bars.

reported specific investment cost of TerraNova compared to C-Green, motivates in the investment in HTC in S2-2-CHP/-heat-only (incl.ES).

Enhancing the efficiency of WWTPs to the point where they are practically self-sufficient should be concurrent with significant economic benefits. Due to the poor quality of sewage sludge (high water and ash content), energy recovery alone is usually insufficient to motivate the implementation of investment-intensive technologies. It should be noted that in S2, it is expected that the plant needs to replace its thermal dryer, which has a substantial impact on whether or not the HTC can be implemented at the WWTP. Still, most S2 scenarios show small or no

investment opportunity. Conversely, HTC is profitable in S1, despite the plant's investment in a new technology that raises energy requirements. HTC thus offers more economic benefits to WWTPs that are dependent on centralized waste processing plants for sewage sludge treatment, than for those integrated with a combustion facility.

Due to the great impact of investment costs on the economic feasibility of introducing HTC into the sewage sludge treatment process, a more in-depth economic evaluation is recommended where investment related uncertainties, such as interest rate and access to capital, are investigated, as these aspects have been shown to have considerable

impact on the relative performance of the cases.

3.2.1. Sensitivity analysis results

The results of the sensitivity analysis (Fig. 4) show that all HTC-C-Green scenarios, i.e., S1-1 and S2-1-CHP/-heat-only/(incl.ES), exhibit an inverse correlation with the electricity price. This is due to the decreased net electricity output, which means these cases are not economically favored by a high electricity price. In contrast, a higher gate fee and hydrochar price would improve the feasibility of the scenarios, with both S1-1 and S1-2 showing considerable sensitivity to the gate fee. S1-2 also has an inverse correlation with the heat price as the net heat output is lower than in S1R-2, while the rest of the scenarios' investment opportunities positively correlates with heat and electricity market prices.

The impact of the P revenue on the economic feasibility in the HTC-TerraNova scenarios (S1-2, S2-2-CHP/-heat-only/(incl.ES)) was found to be insignificant. Consequently, the annual specific investment margin has low sensitivity toward P price, which could bring an opportunity for the sludge-based P to be sold at a lower price than mineral-based fertilizer and benefit the marketability of sludge-based P. Overall, the amount of recovered P and its revenue in the current market are insignificant; P recovery is insufficient to provide sufficient investment motivation for the adoption of recycling techniques. Therefore, legislation that demands P recovery but doesn't provide financial supports is unlikely to result in effective P recovery solutions.

Energy and investment intensive technology have no investment opportunity in sewage sludge treatment chains, unless boundary conditions such as energy and disposal costs for sewage sludge increase. Although HTC offers an alternative for energy-intensive drying (in S2), the implementation opportunity of HTC into a WWTP is higher in S1. The results are influenced by the assumption that the thermal dryer in S2 needs to be replaced; otherwise, it is possible that the replacement may not be motivated by economic considerations. The integration of AD and combustion is limited to locations with high population density, and the opportunity for integration of AD + HTC + combustion is thus also limited due to the same limiting factor. Whereas, transportation of wet sludge is a common challenge among WWTPs, and AD + HTC integration not only solves the challenge but also has a significant investment opportunity.

HTC has been previously reported as a suitable pathway to immobilize HMs and remove pharmaceutical contaminants (Hämäläinen et al., 2021; Tasca et al., 2022). For this reason, hydrochar has a better chance of being marketable as a product compared to sewage sludge, which is considered a waste. In order to assess the implementation potential of HTC for sewage sludge, more in-depth investigations are required concerning i) detailed economic performance, ii) regulatory framework, and iii) hydrochar market formation.

4. Conclusions

By techno-economic analysis of introducing HTC in (i) a WWTP with AD, or (ii) a WWTP with the combination of AD and combustion, this study showed that the net output of heat, electricity, or both could be improved, depending on the energy demand of the HTC process. Using wet oxidation to cover the HTC's heat demand entails a high investment cost and decreases the net electricity output. Therefore, this option is economically unattractive under the conditions investigated here. However, adding HTC to a WWTP with AD results in a significant investment opportunity because it i) improves the biogas production, ii) avoids disposal of sewage sludge and its related costs compared to the business-as-usual practice, and iii) generates a new hydrochar revenue. In this case, the investment opportunity is highly sensitive to both the hydrochar price and the disposal cost. The replacement of the thermal dryer with HTC, when process water of the HTC is directly returned to the AD, shows a positive investment opportunity. It should be noted that replacing the thermal dryer with HTC as pre-treatment for a combustion

process could impair electricity production if the AD is not integrated with the HTC and combustion, because the thermal dryer operates by a low-temperature heat source while HTC requires steam. Although HTC uses less energy than a thermal dryer, its energy advantages only lead to a small investment opportunity because of the high investment cost. The investment opportunity can be improved by allowing for co-combustion of the produced hydrochar and external digested sludge, under the condition that the plant receives a gate fee for processing the external sludge. Phosphorus revenue has insignificant effects on the economic feasibility of implementing HTC. This could actually provide an opportunity for marketing sludge-based phosphorus as the easily recovered phosphorus constitutes a by-product from the process, and could as such be sold at a competitive price, without additional investment requirements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.08.006.

References

Akbari, M., Oyedun, A.O., Kumar, A., 2019. Comparative energy and techno-economic analyses of two different configurations for hydrothermal carbonization of yard waste. Bioresour. Technol. Rep. 7, 100210 https://doi.org/10.1016/j.biteb.2019.100210.

Aragón-Briceño, C., Ross, A.B., Camargo-Valero, M.A., 2017. Evaluation and comparison of product yields and bio-methane potential in sewage digestate following hydrothermal treatment. Appl. Energy 208, 1357–1369. https://doi.org/10.1016/j.apenergy.2017.09.019.

Aragón-Briceño, C.I., Ross, A.B., Camargo-Valero, M.A., 2021. Mass and energy integration study of hydrothermal carbonization with anaerobic digestion of sewage sludge. Renew. Energy 167, 473–483. https://doi.org/10.1016/j.renene.2020.11.103.

Bagheri, M., Öhman, M., Wetterlund, E., 2022. Techno-Economic Analysis of Scenarios on Energy and Phosphorus Recovery from Mono- and Co-Combustion of Municipal Sewage Sludge. Sustainability 14 (5), 2603. https://doi.org/10.3390/su14052603.

Brinkmann, T., Santonja, G.G., Yükseler, H., Serge Roudier, L.D.S., 2016. Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector. Off. J. Eur. Union. Luxembourg.

C-Green, 2022. C-Green OxyPower HTC™ [WWW Document]. URL https://www.c-green.se/oxypower-htc.

Czerwińska, K., Śliz, M., Wilk, M., 2022. Hydrothermal carbonization process: Fundamentals, main parameter characteristics and possible applications including an effective method of SARS-CoV-2 mitigation in sewage sludge. A review. Renew. Sustain. Energy Rev. 154 https://doi.org/10.1016/j.rser.2021.111873.

Eboh, F.C., Andersson, B.-åke, Richards, T., 2019. Economic evaluation of improvements in a waste-to-energy combined heat and power plant. Waste Manag.

Egle, L., Rechberger, H., Krampe, J., Zessner, M., 2016. Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. Sci. Total Environ. 571, 522–542. https://doi.org/10.1016/j.scitotenv.2016.07.019.

Escala, M., Zumbühl, T., Koller, C., Junge, R., Krebs, R., 2013. Hydrothermal carbonization as an energy-efficient alternative to established drying technologies for sewage sludge: A feasibility study on a laboratory scale. Energy and Fuels 27, 454–460. https://doi.org/10.1021/ef3015266.

Faragò, M., Damgaard, A., Madsen, J.A., Andersen, J.K., Thornberg, D., Andersen, M.H., Rygaard, M., 2021. From wastewater treatment to water resource recovery: Environmental and economic impacts of full-scale implementation. Water Res. 204 https://doi.org/10.1016/j.watres.2021.117554.

Ferrentino, R., Merzari, F., Fiori, L., Andreottola, G., 2020. Coupling hydrothermal carbonization with anaerobic digestion for sewage sludge treatment: Influence of HTC liquor and hydrochar on biomethane production. Energies 13. https://doi.org/10.3390/en13236262.

Gao, N., Kamran, K., Quan, C., Williams, P.T., 2020. Thermochemical conversion of sewage sludge: A critical review. Prog. Energy Combust. Sci. 79, 100843 https://doi.org/10.1016/j.pecs.2020.100843.

Gerner, G., Meyer, L., Wanner, R., Keller, T., Krebs, R., 2021. Sewage Sludge Treatment by Hydrothermal Carbonization: Feasibility Study for Sustainable Nutrient Recovery and Fuel Production. Energies 14, 2697. https://doi.org/10.3390/en14092697.

Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z.P., Wang, X., Wu, J., Li, F., 2017. The feasibility and challenges of energy self-sufficient wastewater treatment plants. Appl. Energy 204, 1463–1475. https://doi.org/10.1016/j.apenergy.2017.02.069.

Hämäläinen, A., Kokko, M., Kinnunen, V., Hilli, T., Rintala, J., 2021. Hydrothermal carbonisation of mechanically dewatered digested sewage sludge—Energy and nutrient recovery in centralised biogas plant. Water Res. 201 https://doi.org/10.1016/j.watres.2021.117284.

Havukainen, J., Saud, A., Astrup, T.F., Peltola, P., Horttanainen, M., 2022. Environmental performance of dewatered sewage sludge digestate utilization based on life cycle assessment. Waste Manag. 137, 210–221. https://doi.org/10.1016/j.wasman.2021.11.005.

Hedayati Marzbali, M., Kundu, S., Patel, S., Halder, P., Paz-Ferreiro, J., Madapusi, S., Shah, K., 2021. Hydrothermal carbonisation of raw and dewatered paunch waste: Experimental observations, process modelling and techno-economic analysis. Energy Convers. Manag. 245, 114631 https://doi.org/10.1016/j.enconman.2021.114631.

HUBER technology, 2021. Sludge2energy: Concepts of Thermal Sewage Sludge Utilisation. Berching.

HUBER technology, 2022. HUBER Belt Dryer BT [WWW Document]. URL https://www.huber.de/fileadmin/01_products/04_sludge/04_trocknen/02_bt/pro_bt_en.pdf.

Ischia, G., Fiori, L., 2021. Hydrothermal Carbonization of Organic Waste and Biomass: A Review on Process, Reactor, and Plant Modeling. Waste and Biomass Valorization 12, 2797–2824. https://doi.org/10.1007/s12649-020-01255-3.

Jupp, A.R., Beijer, S., Narain, G.C., Schipper, W., Slootweg, J.C., 2021. Phosphorus recovery and recycling-closing the loop. Chem. Soc. Rev. 50, 87–101. https://doi.org/10.1039/d0cs01150a.

Jurczyk, M., Mikus, M., Dziedzic, K., 2016. Flue Gas Cleaning in Municipal Waste-To-Energy Plants – Part I. Infrastruct. Ecol. Rural Areas 1179–1193. https://doi.org/10.14597/infraeco.2016.4.1.086.

Kilkovsky, B., Stehlik, P., Jegla, Z., Tovazhnyansky, L.L., Arsenyeva, O., Kapustenko, P. O., 2014. Heat exchangers for energy recovery in waste and biomass to energy technologies - I. Energy recovery from flue gas. Appl. Therm. Eng. 64, 213–223. https://doi.org/10.1016/j.applthermaleng.2013.11.041.

Lucian, M., Fiori, L., 2017. Hydrothermal carbonization of waste biomass: Process design, modeling, energy efficiency and cost analysis. Energies 10. https://doi.org/10.3390/en10020211.

Marin-Batista, J.D., Mohedano, A.F., Rodríguez, J.J., de la Rubia, M.A., 2020. Energy and phosphorous recovery through hydrothermal carbonization of digested sewage sludge. Waste Manag. 105, 566–574. https://doi.org/10.1016/j.wasman.2020.03.004.

Mayer, F., Bhandari, R., Gäth, S.A., 2021. Life cycle assessment of prospective sewage sludge treatment paths in Germany. J. Environ. Manage. 290 https://doi.org/10.1016/j.jenvman.2021.112557.

Medina-Martos, E., Istrate, I., Villamil, J.A., Dufour, J., 2020. Techno-economic and life cycle assessment of an integrated hydrothermal carbonization system for sewage sludge. J. Clean. Prod. J. 277, 122930 https://doi.org/10.1016/j.jclepro.2020.122930.

Merzari, F., Langone, M., Andreottola, G., Fiori, L., 2019. Methane production from process water of sewage sludge hydrothermal carbonization. A review. Valorising sludge through hydrothermal carbonization, Critical Reviews in Environmental Science and Technology. Taylor & Francis. https://doi.org/10.1080/10643389.2018.1561104.

Merzari, F., Goldfarb, J., Andreottola, G., Mimmo, T., Volpe, M., Fiori, L., 2020. Hydrothermal carbonization as a strategy for sewage sludge management: Influence of process withdrawal point on hydrochar properties. Energies 13. https://doi.org/10.3390/en13112890.

Neuwahl, F., Cusano, G., Benavides, J.G., Holbrook, S., Serge, R., 2019. Best Available Techniques (BAT) Reference Document for Waste Incineration, Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control).

Nord Pool, 2021. Market data [WWW Document]. URL https://www.nordpoolgroup.com/Market-data1/Dayahead/Area-Prices/SE/Yearly/?view=table (accessed 8.26.20).

Oladejo, J., Shi, K., Luo, X., Yang, G., Wu, T., 2019. A review of sludge-to-energy recovery methods. Energies 12, 1–38. https://doi.org/10.3390/en12010060.

Ovsyannikova, E., Arauzo, P.J., Becker, G.C., Kruse, A., 2019. Science of the Total Environment Experimental and thermodynamic studies of phosphate behavior during the hydrothermal carbonization of sewage sludge. Sci. Total Environ. 692, 147–156. https://doi.org/10.1016/j.scitotenv.2019.07.217.

Qiao, W., Yan, X., Ye, J., Sun, Y., Wang, W., Zhang, Z., 2011. Evaluation of biogas production from different biomass wastes with/without hydrothermal pretreatment. Renew. Energy 36, 3313–3318. https://doi.org/10.1016/j.renene.2011.05.002.

Rebling, T., Oldhafer, N., Klonk-Markowis, F., Hintz, D., 2020. Hydrothermale Carbonisierung (HTC) als Alternative zur Klärschlammtrocknung ? Eine energetische Betrachtung für Projekte zur Klärschlammmonoverbrennung. Umwelttechnik & Ingenieure GmbH.

Reißmann, D., Thrän, D., Blöhse, D., Bezama, A., 2020. Hydrothermal carbonization for sludge disposal in Germany: A comparative assessment for industrial-scale scenarios in 2030. J. Ind. Ecol. 25, 1–15. https://doi.org/10.1111/jiec.13073.

Riedel, G., Koehler, R., Poerschmann, J., Kopinke, F.D., Weiner, B., 2015. Combination of hydrothermal carbonization and wet oxidation of various biomasses. Chem. Eng. J. 279, 715–724. https://doi.org/10.1016/j.cej.2015.05.086.

Rom, S., Libra, J., Berge, N., Sabio, E., Ro, K., Li, L., Ledesma, B., Bae, S., 2018. Hydrothermal Carbonization: Modeling, Final Properties Design and Applications: A Review. Energies 11, 1–28. https://doi.org/10.3390/en11010216.

Rulkens, W., 2008. Sewage sludge as a biomass resource for the production of energy: Overview and assessment of the various options. Energy and Fuels 22, 9–15. https://doi.org/10.1021/ef700267m.

Schnell, M., Horst, T., Quicker, P., 2020. Thermal treatment of sewage sludge in Germany: A review. J. Environ. Manage. 263, 110367 https://doi.org/10.1016/j.jenvman.2020.110367.

Seiple, T.E., Coleman, A.M., Skaggs, R.L., 2017. Municipal wastewater sludge as a sustainable bioresource in the United States. J. Environ. Manage. 197, 673–680. https://doi.org/10.1016/j.jenvman.2017.04.032.

Shen, Y., 2020. A review on hydrothermal carbonization of biomass and plastic wastes to energy products. Biomass Bioenergy 134, 105479. https://doi.org/10.1016/j.biombioe.2020.105479.

Silva Thomsen, L.B., Anastasakis, K., Biller, P., 2022. Wet oxidation of aqueous phase from hydrothermal liquefaction of sewage sludge. Water Res. 209 https://doi.org/10.1016/j.watres.2021.117863.

Tasca, A.L., Vitolo, S., Gori, R., Mannarino, G., Raspolli Galletti, A.M., Puccini, M., 2022. Hydrothermal carbonization of digested sewage sludge: The fate of heavy metals, PAHs, PCBs, dioxins and pesticides. Chemosphere 307, 135997. https://doi.org/10.1016/j.chemosphere.2022.135997.

TerraNova Energy GmbH, 2022. Process Flow TerraNova@ UItra with integral Phosphorous-Recovery.

TerraNova Energy, 2022. TerraNova Energy Sustainablity [WWW Document]. URL https://www.terranova-energy.com/en/sustainablity/.

Towler, G., Sinnott, R., 2021. Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design, Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design. https://doi.org/10.1016/B978-0-12-821179-3.01001-3.

Vamvuka, D., Alexandrakis, S., Galetakis, M., 2019. Combustion performance of sludge from a wastewater treatment plant in fluidized bed. Factorial modeling and optimization of emissions. Front. Energy Res. 7, 1–10. https://doi.org/10.3389/fenrg.2019.00043.

Wang, L., Chang, Y., Li, A., 2019a. Hydrothermal carbonization for energy-efficient processing of sewage sludge: A review. Renew. Sustain. Energy Rev. 108, 423–440. https://doi.org/10.1016/j.rser.2019.04.011.

Wang, L., Chang, Y., Liu, Q., 2019b. Fate and distribution of nutrients and heavy metals during hydrothermal carbonization of sewage sludge with implication to land application. J. Clean. Prod. 225, 972–983. https://doi.org/10.1016/j.jclepro.2019.03.347.

Weiner, B., Breulmann, M., Wedwitschka, H., Fühner, C., Kopinke, F.D., 2018. Wet Oxidation of Process Waters from the Hydrothermal Carbonization of Sewage Sludge. Chemie-Ingenieur-Technik 90, 872–880. https://doi.org/10.1002/cite.201700050.

Wirth, B., Reza, T., Mumme, J., 2015. Influence of digestion temperature and organic loading rate on the continuous anaerobic treatment of process liquor from hydrothermal carbonization of sewage sludge. Bioresour. Technol. 198, 215–222. https://doi.org/10.1016/j.biortech.2015.09.022.

Young, A.F., Villardi, H.G.D., Araujo, L.S., Raptopoulos, L.S.C., Dutra, M.S., 2021. Detailed Design and Economic Evaluation of a Cryogenic Air Separation Unit with Recent Literature Solutions. Ind. Eng. Chem. Res. 60, 14830–14844. https://doi.org/10.1021/acs.iecr.1c02818.

Zhao, P., Shen, Y., Ge, S., Yoshikawa, K., 2014. Energy recycling from sewage sludge by producing solid biofuel with hydrothermal carbonization. Energy Convers. Manag. 78, 815–821. https://doi.org/10.1016/j.enconman.2013.11.026.