RESEARCH AND ANALYSIS

Hydrothermal carbonization for sludge disposal in Germany

A comparative assessment for industrial-scale scenarios in 2030

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Abstract

The efficient use of biogenic residues can make a significant contribution to increase resource efficiency. Due to its high energy efficiency, hydrothermal carbonization (HTC) is being discussed as a potentially suitable technology for particularly wet and sludgy biogenic residues. In Germany, however, it has not yet been established at industrial continuous operation. Among others, this is due to missing solutions for the economic treatment of the high organic loads in the liquid by-product and insufficient knowledge on long-term processing. Nevertheless, it is still expected that HTC could be able to contribute in the future, especially for sewage sludge disposal. Whether and under what conditions this could be the case is the subject of this study. The competitiveness of modeled cases for industrial sewage sludge HTC, which address different future paths, compared to thermal sludge treatment is investigated by using a multi-criteria instrument. Results show that HTC can only compete with the reference technology if certain framework conditions are given. Particularly, an efficient phosphorus recycling should be integrated and the production costs of the solid product should be at least less than €325 per metric ton according to this case study. The treatment performance of the liquid phase should be as high as possible whereby costs for further treatment equipment should be minimized, so that mentioned productions costs are not exceeded. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
hydrothermal carbonization, industrial ecology, multi-criteria decision-making, sludge disposal, technology assessment

1 | INTRODUCTION

With the latest sustainability strategy, the German Federal Government has set various goals for climate and resource protection (Bundesregierung, 2016). For example, annual greenhouse gas emissions are to be reduced by 55% in 2030 compared with 1990 levels and primary energy consumption by 50% in 2050 compared with 2008 levels. To reach these goals, among others, the recycling of limited raw materials is aimed to reduce the use of primary raw materials (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). The sustainable production of biomass and their conversion into

food, feed, bio-based products, and bioenergy is another central aim, which is often summarized as "bio-economy" (European Commission, 2012). To increase resource efficiency, the gradual recycling and multiple use of natural resources is being pursued (BMEL, 2014). All this requires also the more efficient use of biogenic residues.

Considering the explained background, hydrothermal carbonization (HTC) is currently being discussed as a potentially suitable conversion technology for the treatment of biogenic residues with high water content (Heidari, Dutta, Acharya, & Mahmud, 2018; Reißmann, Thrän, & Bezama, 2018; Wang, Zhai, Zhu, Li, & Zeng, 2018). HTC is a thermochemical process that produces a solid carbon product. Liquid and gaseous by-products are also produced (Medick, Teichmann, & Kemfert, 2017). In current practice (pilot plants), the reaction usually takes place continuously or in a batch process at 200–210°C, 20–25 bar, and within 3–6 hr of residence time (Anderer, 2012; Blümel et al., 2015; Kusche & Ender, 2018). One of the convincing features of HTC is its high energy efficiency. Since water is used as reaction medium anyway, energy- and cost-intensive drying of the substrate prior to the process is not necessary (Escala, Zumbühl, Koller, Junge, & Krebs, 2013). However, there are currently some obstacles that hinder the industrial application of HTC in Germany. In particular, the disposal of the liquid by-product (so-called process water) requires a cost-efficient treatment, which has not yet been conclusively developed (Fettig et al., 2018). Additionally, experiences in industrial continuous operation are missing in Germany so far (Reißmann et al., 2018). Nonetheless, it is expected that HTC may offer a potential alternative in the treatment of sewage sludge (Reißmann, Thrän, & Bezama, 2018a). Particularly, due to adjustments to the fertilizer law (BMUB, 2017) and the sewage sludge ordinance (BMJV, 2017), alternative sludge utilization options with integrated phosphorus recovery will gain in importance in the future.

Whether hydrothermal processes (HTP) can contribute to the future resource efficient treatment of biogenic residues in Germany is currently difficult to assess. Therefore, with previous studies, potentials and obstacles for the development of HTP in Germany were identified by means of a literature review, expert interviews, and a SWOT analysis (Reißmann et al., 2018; Reißmann et al., 2018a). Based on these studies and further representative expert assessments, which were collected through a Delphi survey, three future paths for the development of HTP in Germany until 2030 were constructed. The expert panel of the Delphi survey consisted on various stakeholder groups: science and research (65.5%), business (27.3%), associations and NGOs (3.6%), politics and administration (1.8%), and multipliers (1.8%). The focus was on actors from the scientific field, since HTP is mainly known in the research community and most of the experts are part of this community. A high proportion of around 70% of the scientists surveyed have an environmental background. The survey asked questions about the weighting of the criteria and asked the experts to use the analytical hierarchy process (AHP) scale according to Saaty (Saaty, 1990). In addition, questions were asked about various aspects of the future development of HTP in Germany until 2030. Experts should assess events for their relevance, likelihood, and risk of non-entry for successful technology development. The assessment was based on a Likert scale from 1 (not very relevant/likely …) to 5 (very relevant/likely …). The proposed criteria and events were identified by previous formats (workshops, interviews, literature reviews) (Reißmann et al., 2018a; Reißmann, Thrän, & Bezama, 2018b). Using the Fuzzy Delphi Method (FDM) and fuzzy cognitive mapping (FCM), development factors with particularly high relevance and probability of occurrence by 2030 were determined and their connections presented (Reißmann et al., 2018b). As a result, the following scenarios were derived. The scenarios are not intended to predict a certain future but to show a "development funnel", which can help to reduce uncertainty of future decisions within this context.

- *Technological Action Scenario (HTC-TA):* This scenario represents the most likely development by 2030 according to expert assessments and evaluation using FDM and FCM. Accordingly, the available and technically usable substrate volume for HTP and the disposal costs for HTP-relevant residues (e.g., sewage sludge) will increase by 2030. Depending on the individual case, high-performance treatment concepts are used for the process water. Due to increasing experience in industrial continuous operation, learning effects in business management can be observed. This means that if the cumulative output quantity (here: solid product of HTC) is doubled, the production costs are reduced by a factor (so-called learning rate) of a maximum of 30% (Coenenberg, 1999).
- *Legal and Technological Action Scenario (HTC-LTA):* This scenario represents the most relevant development of supporting factors according to expert assessments and evaluation using FDM and FCM. HTP plants are used decentral and integrated into suitable waste and waste water treatment plants. Due to increasing experience in industrial continuous operation, learning effects in business management can be observed (for explanation, see HTC-TA scenario). Products made of HTP with waste and residual materials as substrates are legally permitted as standard fuels. Nutrient recycling (e.g., phosphorus) is basically integrated into HTP.
- *No Action Scenario (HTC-NA):* This scenario represents the probable development path, excluding factors whose non-occurrence poses a particular risk according to expert assessments and evaluations using FDM and FCM. Accordingly, the available and technically usable substrate volume for HTP and the disposal costs for HTP-relevant residues (e.g., sewage sludge) will increase by 2030.

At this point, it should be pointed out that ecological and social factors should also be included for a comprehensive HTC scenario analysis: the long list in Reißmann, Thrän, and Bezama (2020), which calls "life cycle performance" as an ecological factor and "customer acceptance" and "social acceptance" as social factors, has clearly indicated in this regard, as well. However, due to insufficient data, these factors could not be considered in the present analysis.

To clarify to what extent the individual scenarios differ along the HTC process chain and where the system boundary is set, Figure 1 gives an overview of the relevant factors along the different scenarios and their connection to corresponding process steps.
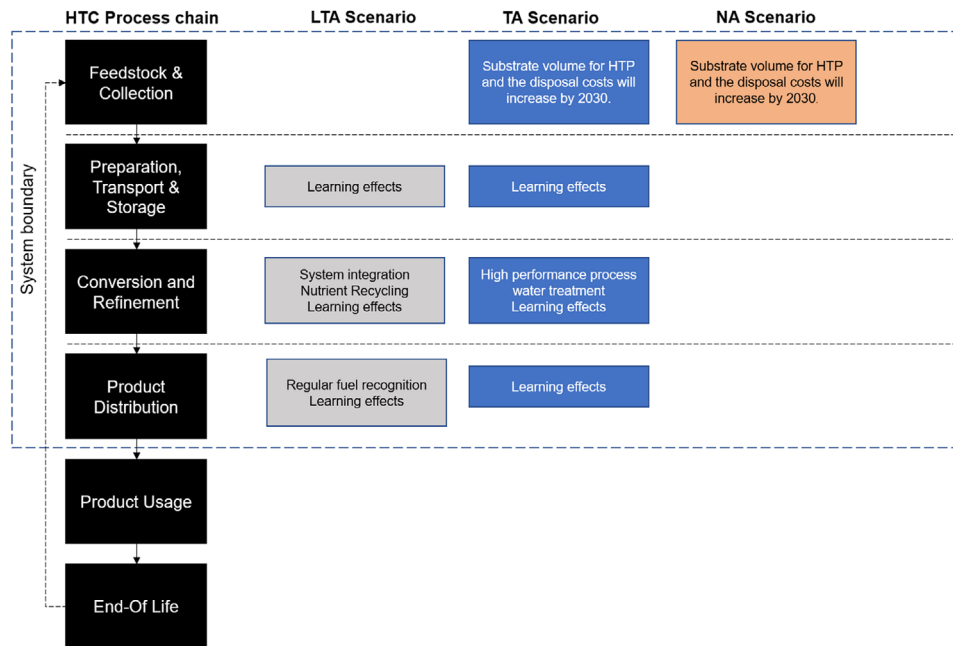
FIGURE 1   System boundary of scenario analysis and corresponding scenario factors along the HTC process chain
Note. HTP = hydrothermal processes; HTC = hydrothermal carbonization; TA = technological action; LTA = legal and technological action; NA = no action.

Parallel to the aforementioned preliminary work, a technology assessment tool for HTP was developed (Reißmann, Thrän, & Bezama, 2018c), which can be used to assess the future paths and compare them to a reference technology. The evaluation tool was specially developed for HTP, which is reflected in the tailored criteria that were derived in a transparent procedure involving various stakeholders (cf. Reißmann et al., 2018a).

This analysis follows on from this previous work. On the one hand, the assessment instrument will be used for the first time to comparatively analyze HTP industrial scale scenarios and, on the other hand, potentially promising development corridors shall be derived for this exemplary case study (which, however, cannot be generalized). The novel contribution of this study is that for the first time (modeled) industrial HTC applications for potential development paths in Germany are quantitatively and comparatively evaluated. Although the literature shows that other studies also consider HTC using multi-criteria assessment tools, no future developments are considered and no geographical focus is set on Germany. For example, Qazi, Abushammala, and Azam (2018) evaluate various waste-to-energy processes, including HTC, using several criteria. Suwelack (2016) also presents an MCA instrument, which is applicable for the evaluation of HTC and describes first steps for implementation. However, a comparative analysis of different industrial HTC applications including possible future developments is not carried out.

The aim is to illustrate how the technology assessment instrument and the scenarios can be used to derive initial benchmarks for the future techno-economic development of HTC at the plant level in Germany. In general, orientation values can also be derived for other areas (e.g., environmental protection), but this study focuses on the techno-economic area. The evaluation is based on data for the semi-technical scale and is also intended to validate the application of the assessment instrument. Further work should substantiate the results, for example, on the basis of further cases, scenarios and by considering further parameters and sensitivities.

2 | METHODS

2.1 | Base case and reference technology

As starting point, a HTC base case for sewage sludge disposal in Germany is created, which reflects a possible technological state in 2030 based on current best available techniques (BAT), but does not yet include any learning effects. Due to the topicality and availability of data, we designed the base case on investigations by Blöhse (2017) on the use of HTC as sludge disposal technology in Germany. These data are based on laboratory tests supported by experiences in the semi-technical scale, which were converted to the large-scale (for detailed information on the data curation and calculation cf. Blöhse, 2017). Since there is a lack of experience in industrial continuous operation and corresponding data sets so far, this analysis represents the most suitable and available data source for the study subject. Accordingly, the technological framework conditions of the base case are shown in Table 1. A visualization of the base case can be found in File S1.

TABLE 1 Base case for sewage sludge HTC representing current BAT

Category	Settings
Substrate input	• Municipal sewage sludge (mechanically dewatered) • 65,000 tons of fresh mass per year • 14,300 tons of dry matter per year (~dry residue content of 22% of the fresh matter) corresponds approximately to a sewage treatment plant with one million population equivalents
Conversion technology	• Continuous operated HTC on an industrial scale • Plant capacity corresponds to substrate input • Processing conditions: 220°C, 2 hr, 15 bar, pH value 7–8, no process optimization
Site and logistics	• HTC plant in a distance of 20 km from the wastewater treatment plant (simplified assumption for central treatment and to exclude assumption "system integration" in the base case) • HTC plant 40 km away from incineration plant
Mass reduction	• 75% of fresh matter input
Product yield	• 68% of dry matter input
COD load	• 278 kg/t dry matter input
Process water treatment	• Anaerobic COD elimination (fermentation), elimination of 70% of COD load
Other by-products for treatment (not considered due to insufficient data)	• Sludge water from first dewatering stage • Exhaust air and condensate (vapors) • HTC process gas
Nutrient recycling	• Excluded in base case
Product use	• Mono incineration in sewage sludge incineration plant as a material to be disposed of

A reference technology representing the current state of the art for sewage sludge treatment serves as a benchmark for the base case and the correspondingly adapted scenario cases. The reference technology for reducing the mass of the sewage sludge is thermal drying up to a dry matter content of 90%, followed by mono-combustion and storage of the phosphorus containing ashes (cf. Blöhse, 2017).

2.2 | Data and assessment criteria

The next step consisted in collecting the necessary information for the technology assessment of the base case. According to Reißmann et al. (2018a), the criteria shown in Table 2 shall be considered when evaluating HTC.

Some of the listed criteria are excluded from the further analysis (marked in bold in Table 2). The TRL is neglected as it is assumed that all cases have reached industrial maturity (i.e., TRL = 9) and thus there are no differences. Due to insufficient and incomparable data, the GHG emissions are also excluded. Comparable GHG balances are necessary for all case studies that are currently not available. GHG calculations already exist for sewage sludge HTC (e.g., Meisel et al., 2019), but not for the case constellation considered here. In order to avoid misinterpretations, this criterion is therefore not considered. The criteria "calorific value of end-product" and "carbon share of end-product" are excluded because they refer to product qualities for potential sales markets or certain fields of application (energy market, carbon sequestration) which are not relevant in the case of sewage sludge disposal.

The decisive factor is that the values of the remaining criteria (i.e., all criteria that have not been marked in bold in Table 2) are calculated or collected on the basis of comparable assumptions. This is reflected in this study, as all the case studies are based on the same basic assumptions (cf. Table 1 for base case assumptions and Table 3 for scenario assumptions) and the same database (i.e., Blöhse, 2017). It should be noted that the criteria are not entirely independent and partly influence each other. However, the holistic presentation of relevant criteria mostly requires this, which is why various studies point out that complete independence of the criteria in practical application is often hardly achievable. Nevertheless, redundancies should be minimized in any case, which is also considered in this assessment (cf. Billig, 2016; Wilkens, 2012).

Regarding investment and operating costs per HTC plant, the following differentiation was assumed. An average of €12 million was considered as the investment cost for HTC plants with simple plant technology, whereas €20 million were considered for HTC plants with complex plant technology. Moreover, 2.5% of the investment was considered as an average of the operating resources and six employees with an average annual salary of €50,000 for a period of 30 years were assumed. The phosphorus recovery is initially excluded within these values and the investment and

TABLE 2 Criteria for technology assessment of HTC (Reißmann et al. 2018a)

Criteria	Description	Unit(s)
Technology readiness level (TRL)	Classification of the level of development of a considered technology according to ISO 16290.	Ordinal scale (1–9)
Production costs per unit	Raw material costs, manufacturing costs, investment and operating costs for one mass unit of the product whereby no further refinement steps are included (e.g., pelletizing). In the following calculation, we differentiate between variable and fixed costs. Investment costs are part of the fixed costs and are calculated in EUR/ton of solid product. Also, energy and amortization are integrated into these calculations, for example, we integrated cost savings for the substitution of methane for electrical and thermal energy into the calculation. Regarding the amortization of investment cost, we referred to Blöhse (2017) as follows: investment: 70% operation technique (cap. = 15 a), 20% building equipment (cap. = 30 a), 10% E-MSR technique (cap. = 10 a), max. time = 30 a. The detailed calculations are part of Reißmann et al. (2020a).	Euro per ton solid product
Conversion efficiency/mass balance	Relation of product output to raw material input (mass related).	Percent of mass unit
Energy efficiency/energy balance	Energetic effort for the production, operation, and reuse (disposal or recycling) of the product (energy balance) in relation to the energetic output of the product (efficiency).	Percent of energy unit
Distance of plant to suitable substrates	Transport distance of suitable substrates from place of occurrence to treatment plant.	Distance in kilometer
Greenhouse-gas (GHG) emissions	Greenhouse-gas emissions occurring through the process steps relating to the system boundaries. For this analysis, system boundaries include transport and conversion steps. All other steps (e.g., product usage) are excluded as there are no difference between the cases.	Global warming potential (CO_2 equivalent)
Pollution of process water	Share of organic substances in process water that occurs after hydrothermal processing.	Chemical oxygen demand in mgO_2/l
Share of recycled phosphorus	Share of phosphorus that is recycled in relation to the total substrate feed-in phosphorus content.	Percent of mass unit
Calorific value of end-product	Maximum usable heat amount through the combustion of the end-product (water free).	Energy unit per mass unit
Carbon share of end-product	Share of carbon in HTC coal in relation to total mass volume of the product.	Percent of mass unit

Note: Criteria in bold are excluded from the further analysis.

resource requirements for the process water treatment are included on an assumption basis. The more complex plant technology is considered for the scenarios with more efficient process water treatment and integrated nutrient recycling (i.e., TA, LTA). For thermal drying, the investment sum is estimated at €5,000,000 over 30 years. Operating costs, staff costs as well as costs for the treatment of vapors and condensate are not included for thermal treatment in order to keep the estimation conservative. The detailed calculations for the individual criteria, broken down according to the various case studies, are available as supporting data in Reißmann, Thrän, Bezama, and Blöhse (2020a) and Supporting Information Files S2 and S3.

2.3 | Scenario factor effects on assessment criteria

The initial criteria values of the base case are then varied according to the scenario assumptions. Table 3 shows the assumptions used to represent the factor and the resulting effects on the individual evaluation criteria. The description of the factors is part of Reißmann et al. (2020a).

2.4 | Technology assessment of HTC cases and reference technology case

Subsequently, all cases are evaluated with the technology assessment tool and compared to the reference technology. The technology assessment will be based on Reißmann et al. (2018c). For details on the methodology, reference is made to this study. According to this, the criteria are first weighted by the analytical hierarchy process (AHP) (Saaty, 1990) and then evaluated comparatively using the technique for order preference by similarity to ideal solution (TOPSIS) (Hwang & Yoon, 1981). Expert assessments were used to weight the criteria according to the AHP. For this

TABLE 3 Scenario factors, assumptions for the presentation of the factor and factor effects on the evaluation criteria

Scenario factors/descriptors	Assumption for representing the factors	Factor effects on assessment criteria
Regular fuel recognition for HTC solid product	The legal framework allows for regular energy sales of the HTC solid product. However, as it is hardly foreseeable from a current perspective whether customers are actually willing to pay a price for the solid product from HTC, this scenario factor is pragmatically included by eliminating the disposal costs at the sewage sludge incineration plant. The reason is that it is assumed that because of the legally guaranteed fuel quality of the solid product, operators of, for example, (heating) power stations to waive the collection of disposal costs for this substitute fuel. From the perspective of the authors, this assumption is most likely as a possible practice.	*Production costs per unit*: Since the product from HTC is now legally considered a fuel, the operators of the sewage sludge incineration plant do not charge disposal costs (here: €80 per ton).
Substrate availability and disposal costs	An increase in the substrate supply is believed to increase the disposal cost of sewage sludge, that is, there will be higher disposal costs (e.g., due to adjustment of contracts). According to a previously conducted expert survey (cf. Reißmann et al., 2020a), the mean substrate increase rate is approx. 13%.	*Production costs per unit*: Disposal costs are assumed to increase proportionally to the 13% increase in substrate amount.
Process water treatment	It is assumed that after anaerobic COD elimination (base case), a further aerobic post-treatment takes place (process water cycle). In addition, a lower pH of 2 (acid addition) is assumed (acidic HTC). However, there is another mass reduction and reduction of the product yield from 11,000 tons to 9,900 tons (assuming the solid residues have dried to dry matter content of 91%).	*Production costs per unit*: Increase of the production costs according to the reduction in mass, whereby reduced transport costs must be included. The cost of process water treatment is increased by 30% of total costs based on own calculations and comparative data of Terranova Energy (Terranova Energy, 2016).

Mass balance: Reduction of the product yield or mass to be disposed of by 10%.

Energy balance: The calorific value increases by 4 MJ/kg for acidic HTC. Based on own calculations, the methane potential increases by 18.6 kWh/t fresh matter and therefore flows into the energy balance as a credit note. Exact values for the reduced energy requirement due to the improved drainage properties could not be found. Nevertheless, in order to take the factor into account, a conservative approach of 5% energy saving in process water treatment is applied.

Pollution of process water: The aerobic post-treatment increases the COD elimination by 10% compared to the base value. Another 10% COD elimination is gained by lowering the pH-value. |
| System integration | The HTC plant is directly integrated into the waste water treatment plant (WWTP). For the reference technology, this is also assumed based on the current state of the art. | *Distance of plant to suitable substrates*: Since the HTC plant is directly integrated into the WWTP, the distance is reduced to a few meters. Based on the paths on the site of a comparable WWTP, we assume 100 m.

Production costs per unit: Transport costs from WWTP to HTC are marginal (100 m) and are therefore neglected, which reduces the production costs. |

(Continues)

TABLE 3 (Continued)

Scenario factors/descriptors	Assumption for representing the factors	Factor effects on assessment criteria
Nutrient recycling	HTC is carried out in a strongly acidic pH range (acidic HTC), which transfers a large part of the phosphorus (<85%) into the liquid phase, that can then be precipitated from it. This requires the addition of sulfuric acid of more than 12 kg per kg of recycled phosphorus (cf. Blöhse, 2017).	*Production costs per unit*: Based on the available data, we charge a lump-sum increase in costs due to the additional acid demand of 30% for the acidic HTC. In general, however, this additional requirement is already included in the assumptions for process water treatment and the corresponding highly acidic process conditions. Since 30% increase is already taken into consideration due to this, it is assumed that the additional acid requirement for nutrient recycling is also included. In addition, further optimization steps for phosphorus precipitation, which can further reduce the acid demand, are conceivable in the future (cf. Blöhse, 2017, p. 128). Nevertheless, additional process steps, increased environmental requirements, other disposal products, and increased expenses in dealing with sulfur levels in solid and liquid phase are needed. In order to take this into account, a lump sum of 15% additional costs is assumed for the total production costs. *Share of recycled phosphorus*: With HTC leaching a phosphorus recovery rate of up to 85% P_{in} is achieved (Blöhse, 2017).
Learning effects	According to the economic principle of the experience curve (Coenenberg, 1999), the inflation-adjusted (real) unit costs decrease constantly as the cumulative production volume increases. Typically, the costs decrease by a maximum of 30% with a doubling of the cumulative output. In this case, we conservatively assume 15% over 10 years (2020–2029). Therefore, considering that the year 2030 is still ongoing in this analysis, learning effects for this year are excluded. In the base case, learning effects are disregarded.	*Production costs per unit*: The production costs per unit decrease by 15% (conservative learning rate), with a doubling of the cumulative output rate in the period under consideration.

purpose, a Delphi survey was conducted among 51 HTP experts (cf. Reißmann et al., 2018b). The Delphi survey went through two rounds. In the first round, there was a response rate of 53% (27 participants) and in the second round (verification of answers from the first round) of 44% (12 participants). The experts were asked to compare the criteria mentioned in Table 2 (and other evaluation criteria relevant for HTP, but are not included in HTC evaluations) according to their relevance (so-called pair-wise comparisons). Using the Excel solver AHPCalc (Goepel, 2013), the criteria weightings were determined on the basis of the survey results (cf. Reißmann et al., 2020a). In addition, the so-called consistency ratio (C.R.) (Saaty, 1987) was calculated to ensure that the weights are consistent. That means, if A > B > C, then A > C must also apply. According to Saaty, a C.R. < 0.1 represents consistency. The weights and their calculations are part of the data files in Reißmann et al. (2020a). The weighted criteria were then transferred to TOPSIS which evaluates a set of decision alternatives. The so-called virtual best and worst case (i.e., best and worst absolute terms of all criteria values) are used as benchmarks to represent the relative merits of the alternatives (Hwang & Yoon, 1981). Thus, the best alternative in relation to other ones that are part of the analysis is calculated.

To further verify the results, a sensitivity analysis is also executed. The parameters disposal costs, learning rates, and cost-efficiency of process water treatment are varied. The specific variations are part Reißmann et al. (2020a) and Supporting Information Files S1, S2, and S4.

3 | RESULTS AND DISCUSSION

3.1 | Comparative assessment for sewage sludge disposal based on single parameters

Based on the assumptions and calculations described, the results for the base case, the scenario cases and the reference technology are given in Table 4.

TABLE 4 Criteria values for base case, scenarios, and reference technology

Criteria	Unit	HTC-Base	HTC-TA	HTC-LTA	HTC-NA	Reference
Minimizing criteria						
Production costs for solid product	EUR/t[a]	410.52	401.36	323.39	420.92	329.77
Conversion efficiency/mass balance[b]	%[c]	70	63	63	70	100
Distance of plant to suitable substrates	km	20	20	0.1	20	0.1[d]
Pollution of process water (treated)	mgO$_2$/l	24340	9787	24340	24340	0[e]
Maximizing criteria						
Energy efficiency/energy balance	%[c]	49	80	78	49	18
Share of recycled phosphorus	% P$_{in}$	0	0	85	0	0

Underlying data used to create this figure can be found in File S2 and the data repository Reißmann et al. (2020).

[a] Based on the resulting end product and therefore on different absolute masses.

[b] In case of disposal, this factor must be minimized, since the mass reduction is then higher. Hence, the amount of waste should be kept to a minimum. If instead the product were sold as a fuel and a profit margin existed, this factor should be maximized.

[c] Based on dewatered and dried sewage sludge for disposal (dry matter content of 91%).

[d] The sewage sludge drying usually happens on site, which is why no transport routes are assumed here in the reference case.

[e] In thermal sewage sludge disposal no HTC comparable liquid phase occurs.

Even without the inclusion of the individual criteria weights, clear differences between the alternatives are obvious. The LTA scenario is the most cost-effective, which is reasoned in learning effects and missing disposal costs. Nevertheless, the difference to the reference technology is relatively low at around €6 per ton.[i] The TA and LTA scenarios each include a 15% learning rate. However, in the TA scenario, the significantly higher investment and operating costs (especially for process water treatment) compared to the base case and the still occurring disposal costs lead to relative high production costs. The NA scenario shows that, despite lower investment costs in simpler plant technology, production costs per unit remain high. This is because of missing learning effects. Due to the increase in disposal costs, this scenario is even worse in production costs than the base case.

Substantial differences are also evident in the mass and energy balances of the alternatives. Since the dried sewage sludge serves as the basis for calculation of the substrate input, the mass conversion of the thermal drying is trivially at 100%. In contrast, all HTC cases lead to a mass reduction, which is considered to be positive because of a reduced disposal volume (e.g., lower transport costs, less specific disposal costs). Energy efficiency is significantly higher in the HTC cases than for thermal sewage sludge drying. This is not surprising since high energy efficiency is one of the key advantages of HTC (cf. Lucian & Fiori, 2017; Wang, Chang, & Li, 2019). Regarding process water pollution, thermal drying has a decisive advantage. Since it does not produce such a by-product, the load value can be set to "0". The reference technology and the LTA scenario are advantageous regarding the distance to suitable substrates, since in both cases the processing of the sewage sludge takes place directly on the WWTP and therefore no transport routes occur. Only the LTA scenario provides a content of recycled phosphorus, as it is the only one that assumes integrated nutrient recycling.

3.2 | Comparative multi-criteria assessment

Although there are some advantages and disadvantages to the cases and scenarios, a clear decision for the optimal alternative is relatively difficult to make, as none of them are convincing in all respects. In addition, the individual criteria have not yet been prioritized. In order to decide which alternative is most advantageous, the criteria may be transferred to the technology assessment tool for HTP. According to the procedure described in Section 2, the TOPSIS efficiency scores presented in Table 5 result accordingly.

The multi-criteria technology assessment shows that the LTA scenario is the preferred alternative in this analysis, followed by the reference technology. In particular, the added value of the multi-criteria analysis, including criteria weighting, is that the relative advantages of the LTA scenario compared to the other HTC scenarios, and the reference case, are very evident now indicated through the high TOPSIS efficiency index. When considering the individual criteria, this strong advantage is not directly recognizable, since, for example, the load of the liquid phase in the LTA scenario is also relatively high.

TABLE 5 TOPSIS efficiency scores for the base case, scenarios, and reference technology

Cases	TOPSIS efficiency	Distance best case	Distance worst case	Rank
HTC-base case	0.14	0.34	0.05	4
HTC-TA scenario	0.27	0.31	0.11	3
HTC-LTA scenario	0.78	0.10	0.36	1
HTC-NA scenario	0.11	0.37	0.04	5
Reference technology	0.59	0.21	0.29	2

Underlying data used to create this figure can be found in File S3 and the data repository Reißmann et al. (2020).

The LTA scenario is probably the most advantageous because it performs best in the key criteria production costs and share of recycled phosphorus, which are both highly weighted. The reference technology is particularly convincing due to the non-occurring process water and the relatively low production costs, which is why it performs quite well. The other three alternatives perform much worse and differ only very slightly to each other. In general, based on the rating, these alternatives are not recommendable.

In the decision-making process, one should first prefer the LTA scenario, whereby this also depends on the framework conditions of the individual decision. For example, if the load of the process water in the LTA scenario is not tolerable for a decision-maker, then the reference technology should be preferred. In that case, however, a higher weighting of the criterion "pollution of process water" would be advisable, or it must be determined a threshold value as K.O. criterion.

The analysis of the modeled case studies on sewage sludge treatment with HTC provides plausible results. It seems reasonable to conclude that only the LTA scenario is advantageous compared to the reference technology, since in particular the lower production costs and the integrated phosphorus recycling represent important advantages. It should be noted, however, that the phosphorus recovery rate in sewage sludge treatment for mass reduction is actually not the target. The target is to achieve a phosphorus content in the remaining solid lower than 20 g of phosphate per kilogram of dry matter (Blöhse, 2017). In this regard, there is a need for further development in the criteria system depending on the objective of the evaluation. In addition, this analysis describes only a modeled example and this is why the results are not transferable. Furthermore, also phosphorus recovery from thermally dried and combusted sludge is possible afterward. This was not included in this case, as the system boundary was set at the delivery of the solid product at the incineration plant. In addition, the aim was to evaluate the system integrated nutrient recycling and not a recycling afterward. However, if the system boundary is set differently and also includes recovery of phosphorus from the ashes, then there would be also a phosphorus recovery rate for thermal drying. Additionally, assuming that legally binding phosphorus recycling from sewage sludge causes a large proportion of the sludge into mono-combustion, it can also be expected that the costs of disposal of the thermal recovery will cease, as the cement industry may be willing to continue to use this substitute fuel in co-combustion. All these factors would change the overall results. However, this requires further assumptions about costs and technology. For example, one could base the recovery of phosphorus from sewage sludge ashes using the so-called Mephrec process, since pilot studies have already been carried out (Reckter, 2019). Hence, further research on this is recommended.

3.3 | Sensitivity analysis

The parameters are only varied for the affected HTC cases. The criteria for the reference technology are kept constant in all analyzes, so that comparability with the initial assessment is ensured. The following assignment to the parameters applies:

- Disposal cost reduction: Basis Case, TA and NA scenarios
- Learning effects: TA and LTA scenarios
- Cost and performance of process water treatment: TA scenario

3.3.1 | Sensitivities for reduced disposal costs

Reducing the disposal costs only influences the production costs for the cases concerned (i.e., base case, TA and NA scenario). The resulting costs are given in Reißmann et al. (2020a) (and also S1 and S4). It should be mentioned, that while in the base case and in the NA scenario the production costs decrease in proportion to the reduction of the disposal costs, this is not the case with the TA scenario. Due to the assumption that the complex process water treatment technology always contributes 30% in addition to the total costs, in this case the costs decrease disproportionately, so that if the disposal costs are completely missing, the production costs of the TA scenario are even higher than in the other two cases. For the reference
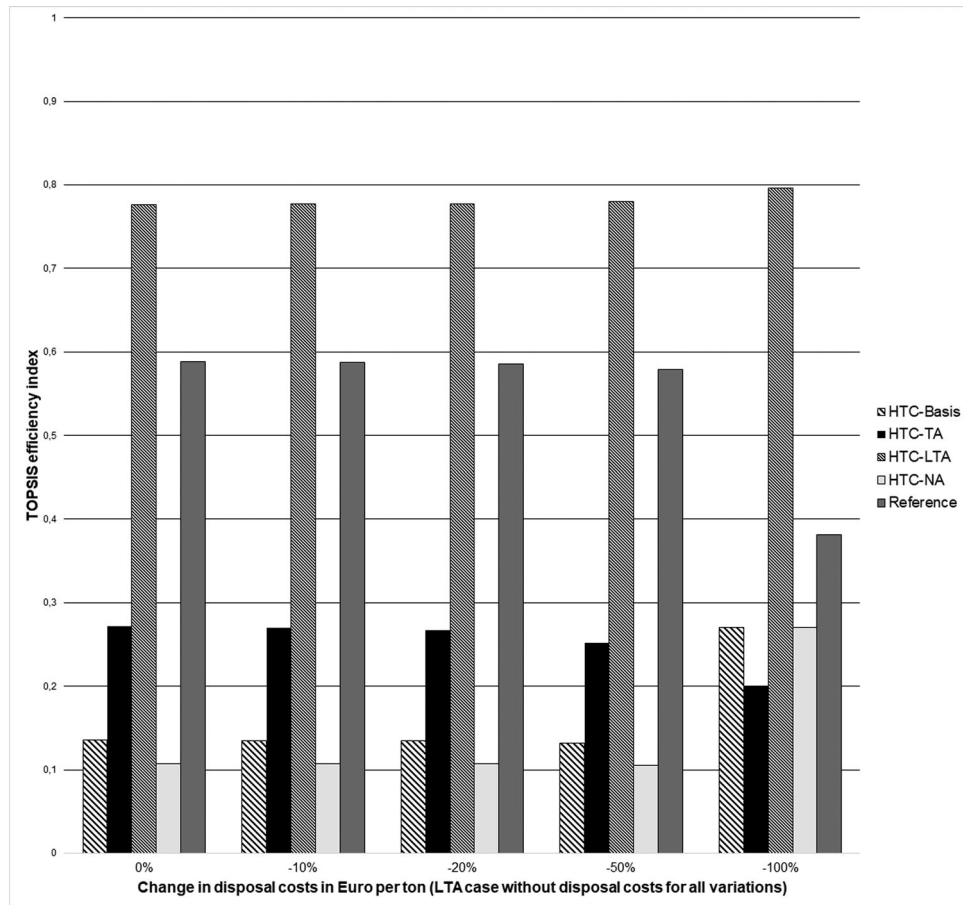
FIGURE 2 TOPSIS efficiency index sensitivities on disposal cost change
Note. HTC = hydrothermal carbonization; basis = basic case without scenario assumptions; TA = technological action scenario; LTA = legal and technological action scenario; NA = no action scenario; TOPSIS = technique for order preference by similarity to ideal solution. Underlying data used to create this figure can be found in Supporting Information Files S1, S2, and S4 and the data repository Reißmann et al. (2020a)

technology, the disposal costs were not varied but instead fully taken into consideration (€80 per ton) as it is assumed that only for HTC disposal cost decrease will occur. In the LTA scenario, the disposal costs were already eliminated for the basis assessment. Transferred to the multi-criteria analysis, the relationship shown in Figure 2 results.

The changes to the initial case (cf. Table 5) in a multi-criteria context are only very slight when reducing the disposal costs. However, if the disposal costs are being dropped, the picture changes significantly. Although the LTA scenario is still most efficient, the gaps of the other scenarios to the reference technology are much lower now. The criteria set of all alternatives is now much clearer, as the distances in the criterion production costs are no longer that strong. When interpreting results from TOPSIS, it is therefore important to consider the entirety of the criteria and their specific weighting and to include all this information into the decision. Basically, it can be stated that by eliminating the disposal costs for the HTC solid product an advantage compared to thermal drying for all alternatives, except the TA scenario, comes closer. Nevertheless, the base case and the NA scenario are still less competitive, also because the non-occurring liquid phase represents a significant advantage of the reference technology.

3.3.2 | Sensitivities for different learning rates

In the case of a variation of the learning rates only the production costs change. For the corresponding cases, the specific values resulting are given in Reißmann et al. (2020a) and S1 as well as S4. For the TOPSIS efficiency indices, the variations according to Figure 3 emerges.

The learning rate has a significant impact on the overall result due to its high cost reduction potential. At lower learning rates in the TA and LTA scenarios, a largely balanced picture emerges, apart from the fact that the high production costs in the TA scenario make it by far the least favorable alternative. It can also be seen that starting at a learning rate of 15%, the LTA scenario makes a strong leap and then represents the most
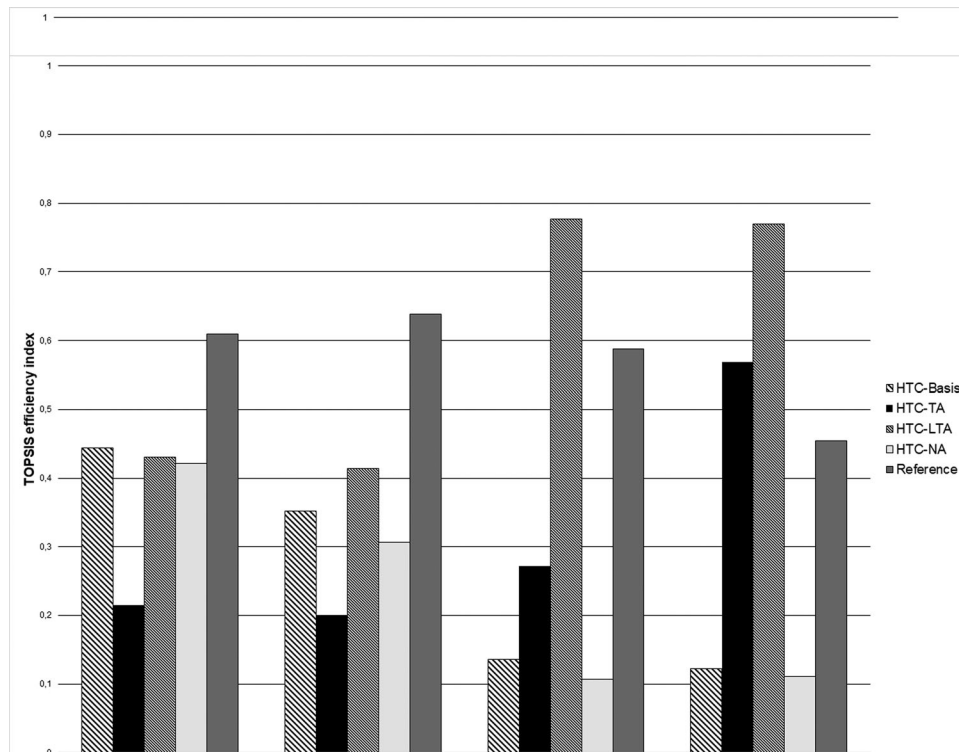
FIGURE 3 TOPSIS efficiency index sensitivities on different learning rates
Note: HTC = hydrothermal carbonization; basis = basic case without scenario assumptions; TA = technological action scenario; LTA = legal and technological action scenario; NA = no action scenario; TOPSIS = technique for order preference by similarity to ideal solution.
Underlying data used to create this figure can be found in Supporting Information Files S1, S2, and S4 and the data repository Reißmann et al. (2020a).

advantageous alternative. At a learning rate of 25%, TA and LTA scenarios are most beneficial. The efficiency indices of the other two HTC cases are decreasing steadily, while the reference case is more robust against an increasing learning rate in the TA and LTA scenario, but also loses relatively high in the efficiency index given the high learning rate of 25%. In general, it can be stated that with a learning rate of 25%, the HTC alternatives in which action is taken are competitive to the reference technology regarding the overall assessment.

3.3.3 │ Sensitivities for cost-efficient process water treatment

Regarding the costs and performance of process water treatment, only the TA scenario is relevant, since only this scenario assumes an additional process water treatment. For the sensitivity analysis, it is first assumed that the performance is increased with additional measures by 50%. However, in the first variant this also leads to 50% additional costs for this cost factor (proportional cost efficiency). In the second variant, again, a performance of 50% is assumed, but with a disproportionate cost increase of 60% and 80% (disproportionate cost increase). In the third variant, the cost increase is assumed to be constant at 50%, but a higher treatment performance of 60%, 80%, and 98% is assumed (disproportionate performance increase). The sensitivities for the production costs and process water treatment performance of the TA scenario are also part of S1 and S4. Figure 4 shows these variants in a multi-criteria context.

None of the considered constellations achieves a significant change in the overall result. Only for "proportional change," it can be observed that the NA scenario and base case improve significantly and become more advantageous than the TA scenario, which now has significantly higher production costs. The other sensitivities show a largely stable picture, the changes are very small. Obviously, the cost increases for process water treatment—even with the highest performance (98%)—always overcompensate all other criteria and lead to the result, that the TA scenario is the worst alternative in all variants. Further considerations in TOPSIS show that even with constant costs in the TA scenario and maximum treatment performance no advantage can be achieved. With a cost reduction of 17% to the initial costs and a consistent highest treatment performance of 98%, the TA scenario is advantageous compared to the reference technology, but is still less favorable than the LTA scenario. Only with a production cost reduction of at least 39% the TA scenario will be advantageous compared to all cases in a multi-criteria context. It is therefore advisable to make process water treatment more cost-effective or to extract and market any by-products (e.g., carbon) that result from the liquid phase.
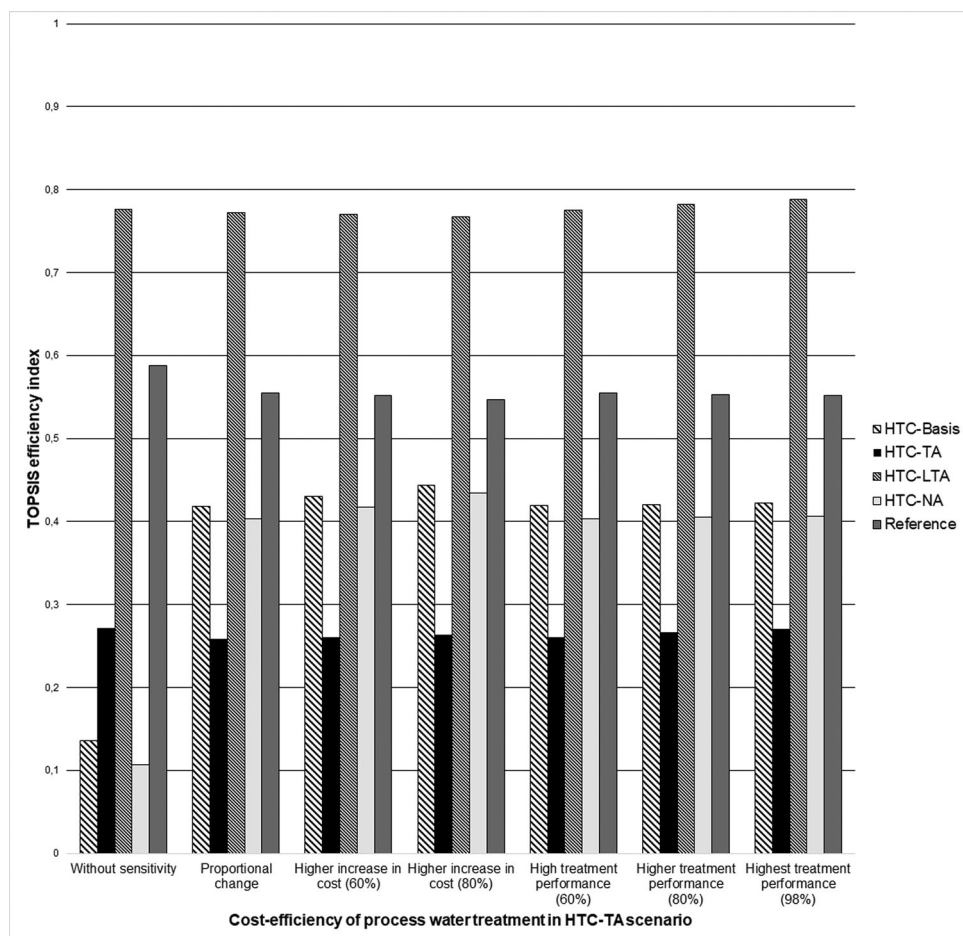
FIGURE 4 TOPSIS efficiency index sensitivities on different costs and treatment performances of process water treatment
Note: HTC = hydrothermal carbonization; basis = basic case without scenario assumptions; TA = technological action scenario; LTA = legal and technological action scenario; NA = no action scenario; TOPSIS = technique for order preference by similarity to ideal solution.
Underlying data used to create this figure can be found in Supporting Information Files S1, S2, and S4 and the data repository Reißmann et al. (2020a).

3.3.4 | Effects on TOPSIS efficiency assuming best parameter combination

Combining the best of the above-mentioned parameters, the LTA scenario dominates (0.79), followed by the TA scenario (0.56) and the reference technology (0.43). The following is assumed:

- Highest cost savings in TA scenario due to learning effects of 25% (assuming that disposal cost increase is overcompensated and thus no included additionally).
- Highest cost savings in LTA scenario due to learning effects of 25%.
- Highest process water treatment performance in TA scenario of 98% with cost savings due to learning effects.
- No disposal costs in base case.

In particular, the learning effects have the strongest effects, since they greatly reduce production costs. However, the high treatment performance in the TA scenario is not sufficient to make this scenario advantageous compared to the LTA scenario, which in turn illustrates the strong dominance of production costs as a decision-making criterion within this case study.

3.4 | Central findings based on MCA and the sensitivity analysis

The production costs have a very strong influence on the overall result, since they are included in the evaluation with almost 40% weight. However, regarding the background of the economic viability of such niche technologies, this is definitely conclusive. Cost-effective competition with the

reference technology is achieved only in the HTC-LTA scenario, but the performance of the process water treatment is insufficient for this case, which is a major barrier. The higher production costs in the other HTC cases always make them unfavorable to the reference technology, even when the process water treatment performance is very high (e.g., 98% in the TA scenario). Basically, only the LTA scenario tends to be competitive with the reference technology, whereby the assumption that there are no disposal costs is largely unrealistic from a current perspective. The TA scenario only becomes competitive when the production costs fall sharply (17–39% cost reduction) and at the same time the process water treatment performance significantly increases. According to this analysis, the base case and the HTC-NA scenario are not competitive in any way. Therefore, they cannot be considered as viable developments for HTC sewage sludge disposal in Germany.

According to this study, the most important parameters for an overall comparability are the production costs, the process water treatment performance, and the degree in phosphorus recycling. In terms of energy and conversion efficiency, HTC is superior to the reference technology in all cases, but this is not sufficient to achieve an overall benefit. The future technological development of sewage sludge HTC should therefore concentrate on the most cost-efficient process water treatment, further potentials for reducing the production costs (e.g., reduction of energy costs through heat waste recovery), and suitable concepts for system-integrated nutrient recycling. In particular, the necessary process water treatment—to tap the exploitation potential and to ensure the legally prescribed treatment targets—represents a point already mentioned many times, which is also considered in other studies as a decisive factor for the techno-economic implementation (e.g., Fettig et al., 2018). Regarding production costs, Lucian and Fiori (2017), for example, cite a range of €157–200 per ton as competitive for the energetic use of the pelleted solid product from HTC. Comparable costs imply this study, whereby the energetic use of the product was not considered. In this study, depending on the specific conditions, production costs per ton HTC solid product of less than €325 are recommended. In the TA scenario, a benefit compared to the reference case was achieved at less than €333 per ton and increased process water treatment performance of 98%. A benefit compared to all alternatives for the TA scenario was achieved for less than €245 per ton and corresponding high process water treatment performance.

Whether HTC represents a suitable alternative to sewage sludge incineration is disputed even beyond the questions on costs and process water treatment. The solid product tends to be unsuitable for the existing stock of sewage sludge incinerators in Germany, as they are designed for higher water contents. According to the current state of knowledge, there is no reference plant for mono-incineration of the highly dewatered sewage sludge from HTC (cf. Remy & Stübner, 2015). In order to increase the quality of the product, qualitative substrates are needed. Often, however, sewage sludge does not represent such a qualitative substrate, which is why HTC research and development may need to address other residues (Brosowski et al., 2016).

In principle, the results should be further validated, for example, by further sensitivity studies, the analysis of other case constellations or by the inclusion of additional parameters (e.g., GHG emissions). The technology assessment tool can be a good aid for this, whereby the interpretation of the results must always be considering the overall context of criteria. A verbal argumentative discussion of the results is therefore obligatory.

4 | CONCLUSION AND IMPLICATIONS

By means of a multi-criteria analysis of sewage sludge HTC on the basis of different scenarios, their competitiveness compared to thermal sewage sludge treatment was considered. The results of this analysis largely confirm the current problems in the field of using HTC for sludge disposal and show that HTC is only advantageous to the thermal drying under very favorable conditions.

The main results of this study can be summarized as follows:

1. Production costs, process water treatment performance, and the proportion of phosphorus recovered have the greatest impact on HTC competitiveness compared to conventional processes.
2. According to this study, the competitive production costs are less than €325 per ton of HTC end product, whereby only the delivery of the product up to mono-combustion and not beyond was considered.
3. The performance of process water treatment should be maximized while keeping costs as minimal as possible. It is recommended to extract by-products from the liquid phase (e.g., carbon) for further sales in order to counteract the high costs.
4. Further potential for reducing production costs lies in system integration (e.g., by using waste heat, considering possible alternatives for outlet products) and the recycling of other nutrients such as nitrogen. However, further research is necessary here, especially based on valid data which is currently not available.
5. A supportive legal framework that in particular allows the use of the HTC product as an energy source can contribute to further cost savings, for example, by no longer incurring disposal costs at the incineration plant. It also ensures greater legal certainty for the actors.
6. Learning effects also ensure substantial cost reductions, whereby this simple business assumption is not based on exact measures but is due to this type of business scenario analysis.

Since the results apply only to the modeled case examples presented here, a generalizability and transferability is not given. Hence, there is a need for further case studies to underpin the results. An application to real plants is stimulated, although in Germany currently no corresponding

HTC plants exist in industrial continuous operation and a corresponding analysis would have to make an assumption-based scaling. Nevertheless, such analyzes are important in order to be able to carry out real tests on the basis of existing technological cases.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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i Throughout the document, the term ton is to be equated with metric ton.

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