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Techno-economic and environmental suitability criteria of hydrothermal processes for treating biogenic residues: A SWOT analysis approach

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Abstract

Biogenic residues are valuable resources that could be utilized through appropriate technologies like hydrothermal processes (HTP) that seem to be suitable to transform wet and sludgy biogenic residues into carbon containing materials and fuels. However, this expectation is not sufficiently evaluated so far which is particularly reasoned in missing criteria to assess HTP as options for the management of biogenic residues. In this paper, we present a structured, transferable and transparent approach for developing techno-economic and environmental suitability criteria for currently discussed HTP concepts using methods from strategy development, especially SWOT analysis. For this, a focus group workshop and expert survey with central stakeholder was carried out and enlarged through an extensive scientific literature review to generate a meaningful information basis. The aim is to identify most relevant criteria to assess HTP to each other and to conventional reference systems which reduces uncertainty for future decisions on the suitability of HTP for treating biogenic residues. The results show that especially the Technology Readiness Level (TRL) is of high importance. Next to this, also the production costs, the product potential, the competitive situation on sales markets and the emissions through the process are of high relevance. In following studies, we want to use these criteria for multi-criteria analysis that will be applied on different scenarios for HTP technology development.

Keywords: Hydrothermal processes (HTP); biogenic residues; expert survey; SWOT-analysis; techno-economic criteria; environmental criteria

1. Introduction

1.1. Background

The efficient use of biogenic resources is an important instrument to support the national and international progress towards sustainable development (BReg, 2016; UN, 2016; UBA, 2014). However, a considerable part of biogenic materials is currently inefficiently used (e.g. energetic usage, despite low heating values) or even not in use, especially because some materials are still considered as waste and not as a resource (cf. Brosowski et al., 2016; Pehlken et al., 2016; Tröger et al., 2013). For example, a recent study calculated a technical potential on unused biogenic residues of 26.9 – 46.9 million metric tons of dry matter [Mg (DM)] just for Germany. A major share of unused residues is identified for animal excreta (9.1 mill. Mg (DM)), sewage sludge (5.7 mill. Mg (DM)) and landscaping materials (2.0 mill. Mg (DM)) (Brosowski, 2015).

In the particular case of sewage sludge, current legal initiatives in most European countries (BReg, 2017; BMEL, 2017; Donatello and Cheeseman, 2013; Stasinakis and Kelessidis, 2012; Werle and Wilk, 2010), as well as logistical and energetic challenges due to its high water content, make the sustainable management of these residual flows an especially challenging task, for which it is important to establish suitable technical alternatives (Werle and Wilk, 2010; Steinle et al., 2009; Zabaniotou and Fytili, 2008).

Exemplary for Germany, the upcoming amendment of the sewage sludge regulation will require an obligatory recycling of phosphorus from the sludges generated in wastewater treatment plants (WWTP). Although this specific obligation depends primarily on the size of the WWTP, most municipal and industrial WWTP will be affected (BReg, 2017). That means, that some sewage sludge treatment possibilities (e.g. direct co-incineration in power plants or with waste) are not suitable anymore, because a phosphorus recovery is not possible with them (cf. Lundin et al., 2004). Also the adjustment of Germany's fertilizer ordinance restricts the future usage of sewage sludge. Due to aggravated thresholds for pollutant and nutrient levels regarding sewage sludge that will be used for agricultural purposes, it is expected that this kind of utilization will decrease on 30% of the current level (Klemm and Glowacki, 2015). For 2013, that decrease refers to 0.5 million Mg [DM] of sewage sludge, according to own calculations based on Destatis (2017).

In summary, there is currently a large potential of unused biogenic residues already available, and it is expected that new material flows will be available in future, especially because of upcoming legal adjustments and further technical developments in the bioeconomy field (Thrän & Bezama, 2017; Hildebrandt et al. 2017). Hence, suitable technologies for a sustainable management of these materials are needed (Bezama, 2016).

1.2. Hydrothermal process platforms

Hydrothermal processes (HTP) are potentially suitable treatment possibilities for the mentioned biogenic materials (Brosowski, 2015), which is also indicated by the increasing scientific (cf. Vogel, 2016; Klemm and Glowacki, 2015; Kruse et al., 2013; Libra et al., 2011) and practical interest (Hallesche Stadt und Wasserwirtschaft, 2015) during the last few years.

HTP aims at converting biomass into gaseous, liquid or solid carbon containing end-products via thermochemical conversion. The procedure needs an aqueous environment for optimal processing, which is why residual materials like sewage sludge and animal excreta are very suitable substrates for applying such platform technologies (Kruse et al., 2013).

Depending on the process’ characteristic parameters (pressure, temperature and residence time) different hydrothermal process types may occur (see Table 1), which can be categorized into three main process types:

(1) **Hydrothermal Carbonization (HTC)** is a coalification process which converts raw biomass into hydro-char, a product that has similar characteristics as fossil coal (Fiori and Lucian, 2017). Hydro-char can be mainly used for energy production (e.g. as fuel or substitute fuel), material applications (e.g. carbon filter) and as fertilizer or soil conditioner in agriculture (Vogel, 2016).

(2) **Hydrothermal Liquefaction (HTL)**, also called hydrous pyrolysis, is a process that converts complex organic structures (such as organic residual streams) into chemicals and crude oil. It mimics the natural geological liquefaction process (Zhang, 2010). The products can be used as liquid fuel for energy production and as substitute to crude oil in the cosmetics sector and chemical industry (Kruse et al., 2013).

(3) **Hydrothermal gasification (HTG)** converts biomass into gas, mainly methane and hydrogen but also other platform chemicals. It mimics the natural gas production process. The products of HTG can be used in the energy sector and chemical industry for different applications (Vogel, 2016; Kruse et al., 2013).

Table 1: Typical temperatures, pressures and residence times for the main types of HTP [adapted from Kruse et al., 2013; Vogel, 2016; Peterson et al., 2008; Boukis et al., 2003]

HTP platform type	Temperature range (°C)	Pressure range (bar)	Typical residence time range (sec)
HTC	160-250	10-30	60-4320
HTL	180-400	40-200	10-240
HTG - Catalytic/low-temperature	350-450	230-400	< 10
HTG - Non-catalytic/high-temperature	> 500	230-400	< 10

1.3. Goal of this work

Although the suitability of specific HTP concepts for the treatment of biogenic residues such as sewage sludge is currently indeed expected, it has not yet been sufficiently evaluated in a sound scientific manner (cf. HTP Innovationsforum, 2017). Among others, to reduce practical uncertainties (e.g. for investors) and deliver comprehensive and objective information for decision makers (e.g. funding institutions) it will be essential to develop scientifically-based evaluation instruments to compare the suitability of HTP concepts for the treatment of biogenic residues with each other (e.g. HTC vs. HTL) and with reference technologies (e.g. biogas production, pyrolysis). This will be also helpful for assessing future technology developments, e.g. by evaluating different scenarios of HTP development and identify most promising directions from a recent point of view.

An important step is the development of suitable criteria that fit to the evaluation of HTP in the mentioned context. Although many technology assessment criteria exist, there are no criteria that were developed for this specific case of assessment. Recent works on technology assessment concentrates on multi-criteria analysis (e.g. Billig, 2016; Generowicz et al., 2011; Nzila et al., 2012), especially because multiple criteria enables the comparison of technologies under consideration of various dimensions (e.g. technological, economical, ecological and social) which is not possible with such one criterion (Huang et al., 2011).

Mostly, the criteria are taken from guidelines for technology assessment (e.g. VDI, 2000) and selected regarding the purpose of the evaluation. For a structured collection, some guidelines and examples exist that recommend selection factors which can be used (cf. Valenzuela-Venegas, 2016; Akadiri and Olomolaiye, 2012; Akadiri et al., 2013). However, the selection of criteria is often executed through the authors of the study without an integration of external estimations. The integration of experts into the criteria development is mostly limited to the step of criteria prioritization. For example, Kamali and Hewage (2017) applied a questionnaire using a 5-point Likert scale to collect professionals' estimations on indicator applicability. Next to such an intuitive prioritization procedure, some studies used the Analytical Hierarchy Process (AHP) to weight criteria through pair-wise comparisons of two criteria carried out by experts (e.g. Bezama et al., 2007; Billig, 2016; Kluczek and Gladysz, 2015).

Although the criteria prioritization or weighting is mostly executed with expert feedback, the initial choice of the criteria set is still very subjective. This is because just a small number of people is involved (mostly just the authors/project team members), which enhances the risk of insufficient selection due to a limited view on the assessment object (e.g. because of professional background). To foster objectivity of such criteria derivation it seems necessary to use a structured approach that integrates also external expert feedback. Although the feedback of one expert is still subjective, the sum of all expert feedback is nearly objective (VDI, 2000).

Hence, the central research aim of this paper is to provide a structured, transferable and transparent approach for the development of dedicated suitability criteria for currently discussed HTP concepts using methods from strategy development including expert feedback. The central method we used is a SWOT (abb. for **S**trengths **W**eaknesses **O**pportunities **T**hreats) analysis, which is an instrument from operations research to develop strategies for organizations (e.g. Kotler et al., 2010). However, SWOT analysis are applied in many different fields today (Helms & Nixon, 2010; Rizzo & Kim, 2005; Valentin, 2001) and this also in a modified and developed way (e.g. Kiurtilla et al., 2000; Yüksel & Dagdeviren 2007).

Through the application of the SWOT analysis it is expected to categorize and connect the estimations of experts in this field with information from literature, and to formulate strategic targets for a successful technology application. A considerable advantage of using the SWOT analysis is that potentials as well as barriers are considered for the target and criteria derivation. This increases the holistic nature of the derived criteria, because the risk of a one-sided concentrating on potentials or barriers is minimized. Based on these targets, criteria for the assessment of "target achievement" can be derived. For example, if the target is "increase process energy efficiency" the corresponding criteria for assessing target achievement will be "process energy efficiency".

2. Methodology

The approach applied in this work consisted of a sequence of eight steps (Figure 1). Although the methodology was developed for the assessment of the suitability of HTP platforms for the management of biogenic residues, the approach can be adopted to other cases of criteria development.

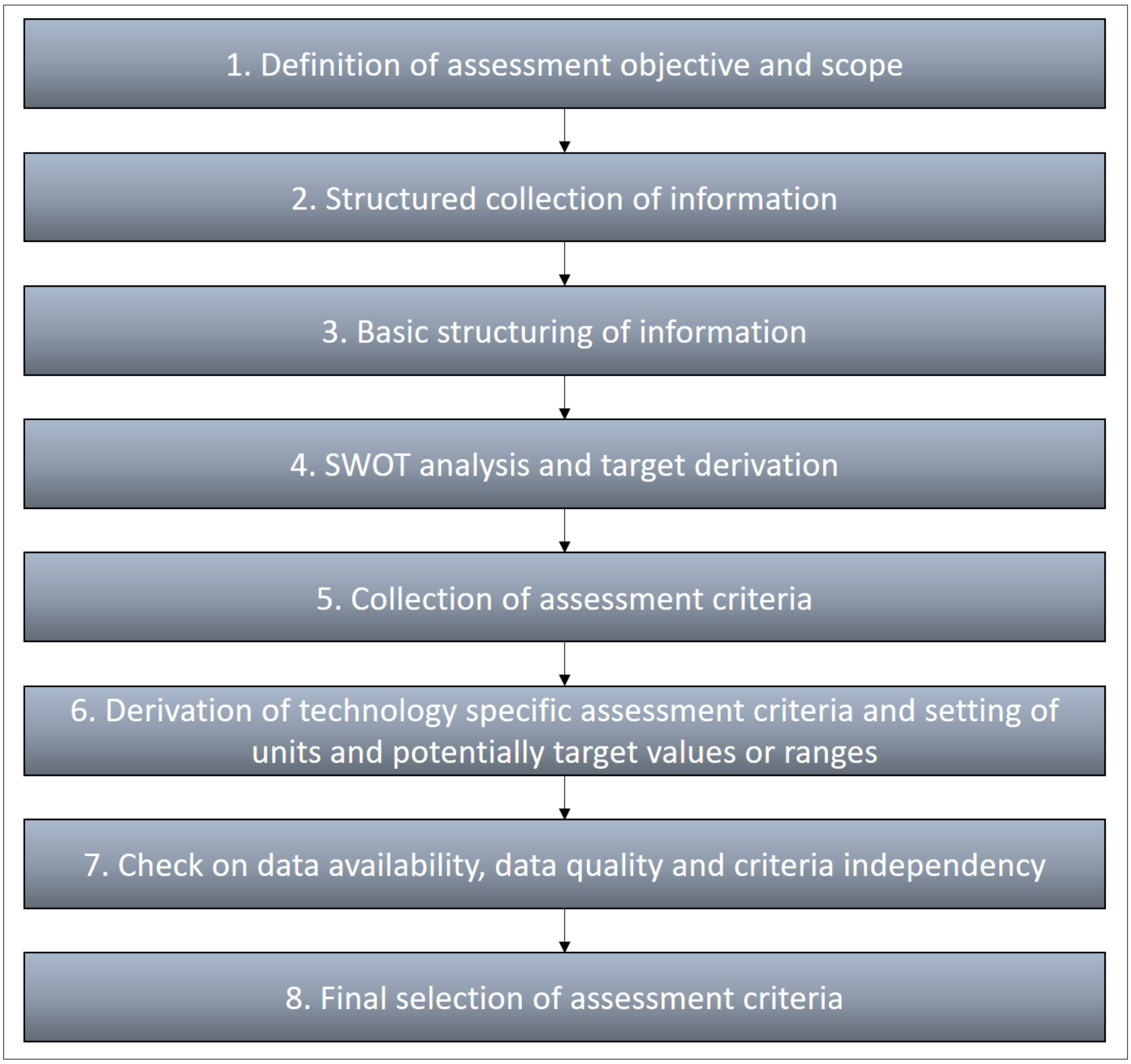

Figure 1: Methodological sequence of criteria development [own illustration]

Step 1: Definition of assessment objective and scope

First, the objective of the assessment must be clearly defined. In this analysis, the objective is to assess the suitability of HTP platforms for the management of biogenic residues. Next to such a basic objective, a clear scope should be determined to set the framework of the analysis. This contains the determination of information on (1) dimensions that shall be addressed: technological, economic, environmental and/or social and (2) spatial scope.

In this paper, the following scope is addressed:

(1) Dimensions: technological, economic and environmental
(2) Spatial scope: Primary Germany, because the expert panel consists mostly of German experts and few experts from Switzerland. However, the literature review also includes international information.

Step 2: Structured collection of information

Several sources were used for collecting the information necessary for this work. The combination of a literature review and formats that consider expert opinions (e.g. workshops, surveys, personal interviews, telephone interviews) is recommended. Through this, also information that are not published as well as opinions from different stakeholder groups could be integrated. Additionally, the objectivity and transparency of the collected information was very high because many different sources of information were taken into consideration.

To identify relevant experts, we used a top-down stakeholder identification, which will be briefly explained. Stakeholder are groups or individuals that are influenced or have an influence on the possibilities of an organization or company to reach its strategic targets (Freeman, 1984). Reed et al. (2009) recommend a structural approach to identify and classify the most relevant stakeholder consisting of a stakeholder identification, categorization and a final inter-connection of the stakeholder. However, this approach can be modified depending on the objective of the analysis. For this work, the authors decided to concentrate on the stakeholder identification as we considered it sufficient for this case. A top-down approach was chosen, which means that the stakeholders were identified through an analytical procedure.

Usually, the typical stakeholder of a technology can be identified through the consideration of information-, material-, financial- and energy flows (Fürst et al., 2004). With this in mind, the following information- and material flow chart with corresponding stakeholders was developed based on charts for conceptual environmental analysis of Frischknecht (2002).

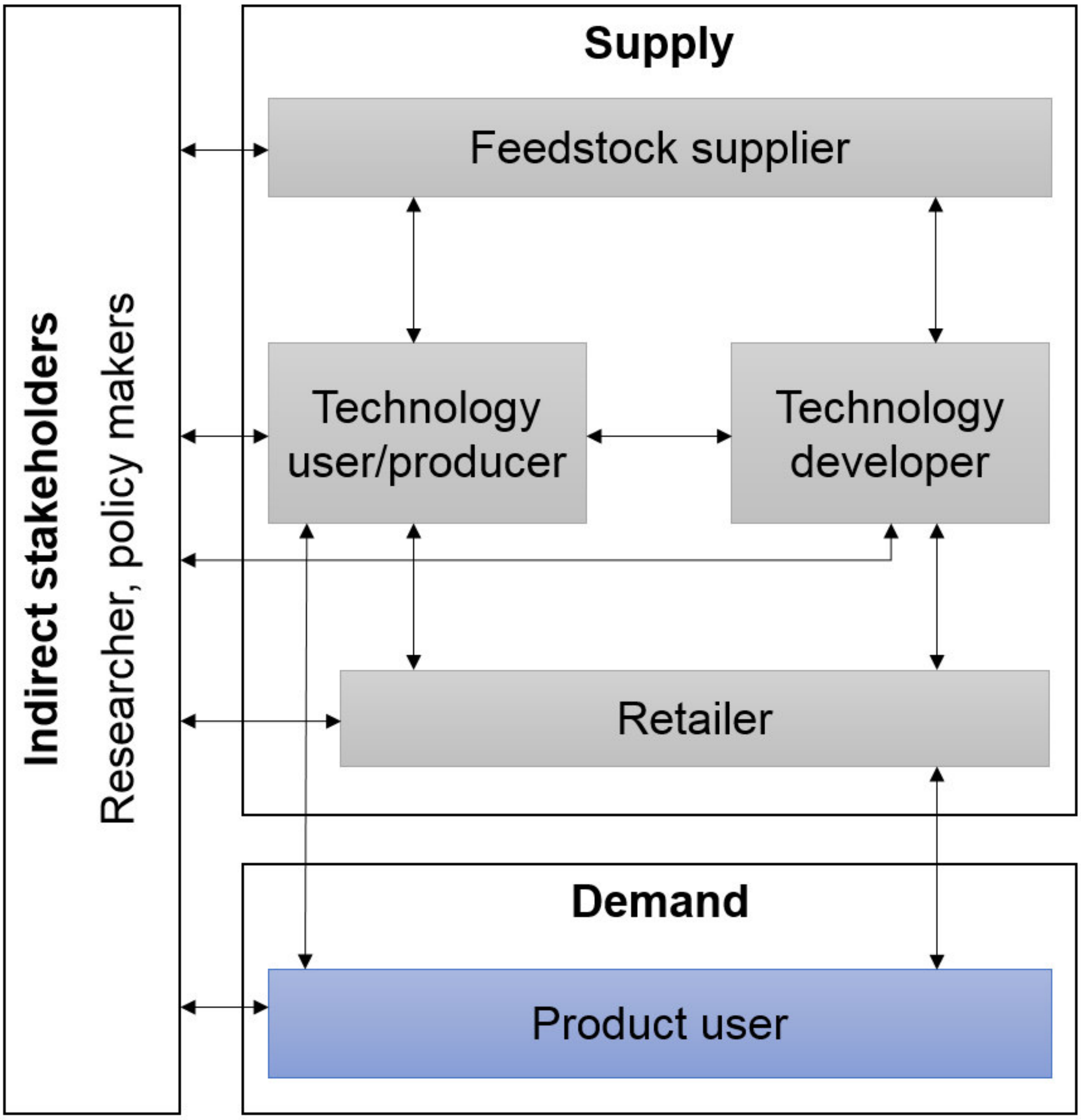

Figure 2: Material flows and information flows for HTP and corresponding stakeholder [adapted from Frischknecht (2002)]

The boxes in figure 2 show the identified stakeholder groups that were considered for the selection of the experts.

As formats for collecting expert opinions, we used a focus group workshop and an expert survey. A total of 41 experts took part in a focus group workshop organized in September 2016 in Leipzig (Germany), through which general information on technological, economic, environmental and legal potentials and barriers of HTP for the management of biogenic residues were collected and discussed. The discussion was open, which means that the experts were asked for general potentials and barriers for every specific dimension as well as other important factors that must be considered without asking for specific details. Additionally, the discussion was introduced with a short presentation illustrating the background. The participants of the focus group workshop were mainly researchers, technology developers and technology user from Germany and Switzerland. To generate a meaningful information basis, it was necessary to include also the other stakeholder. This was carried out through an expert survey. The composition of the survey panel (mostly from Germany) is shown in Table 2. It must be noticed that several participants represent more than one direct stakeholder group which is why the overall survey panel of direct stakeholder includes eight participants. The low participant number is especially due to the novelty of the assessed technology which leads to a low number of experts in field in general.

Table 2: Characterization of expert survey participants

Stakeholder	Requested	Responses	Field of operations	Level of operations
Direct Stakeholders				
Feedstock supplier	3	3	Sewage sludge and agricultural residues	National level
Technology Developer	2	2	Biomass Conversion Technologies	National and international level
Technology User	4	4	Hydrothermal carbonization	Regional and federal level
Retailer	3	2	HTC product distribution	National and international level
Product User	4	2	Agriculture and Energy sector	Regional and international level
Indirect Stakeholders				
Policy Maker	1	1	Environmental Policy	Federal and international level
Researcher	5	4	Biomass Research	National and international level
Total	**22**	**18**		
Response Rate	**82%**			

The expert survey consisted of 13 open formulated questions asking for technological, economic and environmental potentials and barriers of HTP for the treatment of biogenic residues in Germany.

Finally, a review of the available scientific literature (see Reißmann et al., 2018 for more details) was carried out to underpin the results and include also information beyond Germany and Switzerland.

It must be considered that legal assessment criteria will not be developed through this analysis although such information were collected. This is because the criteria derivation will be based on dimensions according to VDI 3780 (VDI, 2000) that focus on technology assessment and do not include legal criteria. However, this information will be considered as frame-setting conditions.

Step 3: Basic structuring of the information

All these sources of information delivered a comprehensive basis on technological, economic, environmental and frame-setting legal conditions of HTP in the context of treating biogenic residues. To separate the most relevant information is seems necessary to use filtering criteria based on the frequency of mentions. Figure 3 illustrates the filtering of information in this analysis. The symbol "≥" means "at least mentioned (by/in)".

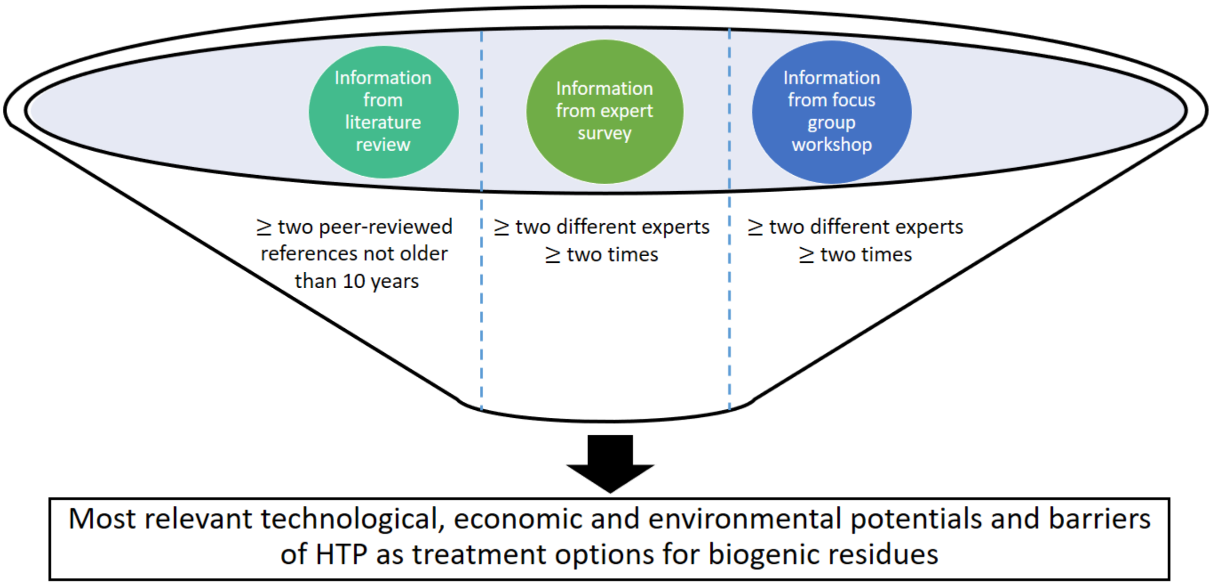

Figure 3: Filtering criteria for selection of most relevant information [own illustration]

The 'filtered' information was afterwards categorized in potentials and barriers for every considered dimension. Depending on the objective of the analysis, other filtering criteria can be used. However, the filtering step is essential to differentiate important from less important information why it should not be skipped.

Step 4: SWOT analysis and target derivation

Through this step, the potentials and barriers were furthermore categorized into strengths, weaknesses, opportunities and threats using a SWOT analysis (cf. Szulecka and Salazar, 2017). Based on the definitions of traditional SWOT analysis (e.g. Rizzo and Kim, 2005; Srivastava et al., 2005), Table 3 shows adapted definitions for strengths, weaknesses, opportunities and threats as well as corresponding key questions which were used in the context of this analysis. The goal of this categorization was to separate internal, which means particular controllable, strengths and weaknesses, from external, which means none controllable, opportunities and threats.

After categorizing the information, the categories were connected through a matrix approach to develop success strategies/targets, on which the assessment criteria were derived. Following strategies/targets are formulated:

- Follow opportunities, which fit to the strengths → *SO-targets*
- Use strengths, to counteract threats → *ST-targets*
- Eliminate weaknesses, to use new opportunities → *WO-targets*
- Develop defenses, to avoid that weaknesses become the aim of threats → *WT-targets*

The derivation of criteria was oriented on their suitability to reach these targets. Hence, the developed assessment criteria refer to advantages (strengths, opportunities) and disadvantages weaknesses, threats) of the technology.

Table 3: Definitions of SWOT analysis categories oriented on Rizzo & Kim (2005) and Srivastava et al. (2005)

SWOT Categories	Short Description	Key questions
Strengths	Internal resources or capacities which enable HTP platforms and the resulting products a potentially successfully market introduction because there are specific advantages in contrast to potentially competitive technological concepts and the resulting products.	• What are the advantages? • What are the factors supporting the technology?
Weaknesses	Internal limitations, problems or shortages which impede a successfully market introduction of HTP platforms and the associated products in the mentioned systemic contexts, because they lead to serious disadvantages regarding competitive technologies and associated products	• What could be improved? • What should be avoided? • What obstacles hinder progress? • Which elements need strengthening?
Opportunities	Mainly external forces that influence the operating environment of the HTP platforms. These external forces could lead to sudden changes on products or technology markets that go along with new opportunities regarding business segments or procurement and sales.	• What benefits may occur? • What changes in usual practice and available technology may occur? • What changes in Government policy may occur? • What changes in standardization may occur? • What changes in socio-economic behaviour may occur?

Threats	Mainly external caused unfavourable situations that hinder HTP platforms to reach the market because of specific barriers and limitations that occur through that.	• Do the relevant stakeholders show their willingness and interest to support the technology? • What external obstacles do the technology platform face? • Is the changing technological and economic environment threatening the technology platforms market success?

Step 5 and 6: Collection of assessment criteria, derivation of target specific criteria, setting of target values and categorization between input and output metrics

Based on the developed targets, criteria for assessing the possibility to reach these targets were derived. For this, established criteria from technology and sustainability assessment were connected to the targets using an arrow/process diagram. Through the usage of established criteria, the connectivity to established methods of technology assessment was guaranteed (cf. Billig, 2016; Kröll, 2007).

The established criteria were collected for the previous defined dimensions (see step 1). In this case, criteria on technology, economy and environment were selected. We used criteria according to the guideline VDI 3780 (VDI, 2000) and from selected literature on technology and sustainability assessment (Billig 2016; Buchholz et al., 2009; Markevičius et al., 2010; Shriberg, 2004; Scheffczik, 2003) to create a comprehensive basis. Table 4 shows the used criteria.

Table 4: Selected general criteria for technological and sustainability assessment

Dimension	Operability	Economy	Environmental quality

Criteria and Sub-Criteria	Technical efficiency
	• degree of efficiency
	  ○ energy
	  ○ material
	• accuracy
	• compatibility with other technologies
		Cost factors
		• production costs
		• life cycle costs
		• microeconomic values (e.g. ROI)
		• cost efficiency
		• external costs
			Emissions
			• pollutants
			  ○ greenhouse gases
			  ○ heavy metals
			• nutrients
			• noise
			• rays

	Feasibility
	• technical know-how
	• availability of materials/substrates
	• effort for feedstock supply
	• type of substrate
	  ○ residues
	  ○ other
		Profitability
		• main products
		  ○ quality
		• by-products
		  ○ quality
		• product diversification
		• price level
		• price development
		• competitive situation
			Resource consumption
			• materials
			  ○ renewable
			  ○ non-renewable
			• land
			• water

	Usability • robustness	Economic stability • project lifetime	Land use change • direct

	• ease of operation • ease of repair	• Technology Readiness Level (TRL)	• indirect
	Safety and resilience • resilience against external impacts (e.g. climate events) • resilience against internal impacts (e.g. corrosion)	Employment generation • number of jobs created • quality of jobs created	Contamination (of objects of protection) • soil • water • air • flora • fauna • human

For the criteria selection, the following principles were used:

(1) Only those criteria were chosen, that are applicable for at least one target,
(2) The chosen criteria were modified (if needed) with regard to the corresponding target.

Also these selection principles can be modified depending on the assessment objective (as defined in step 1).

The results of the comparative selection was a set of assessment criteria that represent the identified targets. To make these criteria measurable, units must be connected to the criteria. If possible (e.g. because legal thresholds exist), also (minimum/maximum) target values or ranges can be set, e.g. specific efficiency values. Next to this, it was recommendable to further categorize the criteria in input and output metrics. This will be useful, if the criteria should be applied for efficiency evaluation, like Data Envelopment Analysis (Charnes et al., 1978) or TOPSIS (Hwang & Yoon, 1981). Such methods need a differentiation between input and output criteria.

Step 7 and 8: Checking data availability, data quality, independency of criteria and selecting final criteria

Data availability and a good quality of data are important factors to ensure the usability of the developed criteria for further assessments as well as a high quality of assessment results. However, this mostly depends on the specific case of evaluation (e.g. specific process design, cost structure etc.) and cannot be decided beforehand. Next to this, also independency between the criteria must be considered. The value of the results of criteria based assessments increases with rising independency, although an absolute independency of all criteria is hardly reachable. According to Billig (2016), independency can be checked through a calculation of specific default parameter for each criterion of the assessed technology concept. If the impact of difference between the technology concepts superimposes the impact of difference of each criterion they can be regarded as sufficiently independent. However, also this independency check depends on the specific assessment case. Some multi-criteria decision-making concepts do not need such an independency, because they already assume dependency of criteria. The

Analytical Network Process (Saaty, 2001) is such a method. Hence, depending on the applied evaluation method the independency check can be perhaps neglected.

An alternative way for a further improvement of the derived assessment criteria set is presented through Cinelli et al. (2016). They recommend proving the criteria set on completeness, reliability and validity based on a criteria ranking through expert estimations and a following correlation analyses which helps to identify parameters of highest interest as well as the connections and dependencies between them.

3. Results

3.1. Essential potentials and barriers of HTP

The described methodology was applied for the development of assessment criteria for the suitability of HTP platforms as treatment options for biogenic residues.

First, the overall information basis (expert survey, focus group workshop and literature review) was filtered through the criteria mentioned in the methods section (step 3) and categorized into technological, economic and environmental potentials and barriers. The results are shown in Tables 5 and 6.

Table 5: Overview of the identified essential potentials of HTP

Category	Potentials	References
Technology		
Feedstock	Unused wet and sludgy material flows available	Brosowski et al., 2016; Greve et al., 2014
	Very suitable treatment option for sewage sludge	Greve et al., 2014; Libra et al., 2011
Conversion/ Processing/ Product Composition	High energy efficiency (esp. because no drying and thickening of wet materials is necessary)	Escala et al., 2013; Škerget et al., 2013
	High energy and carbon content of end-products	Roman et al., 2012; Vogel, 2016
	Integrated phosphorus recycling	Heilmann et al., 2014; Dai et al., 2015
Economy		
Costs	Inter- and cross-sectorial cooperation can reduce overall costs	*
	Decrease in production costs estimated	Jones et al., 2014; Barreiro et al., 2013
Sales	Large product variety	*
Environment		
Environment	HTC-char as potential carbon sink	Libra et al., 2011; Luterbacher et al., 2009
	Global Warming Potential very low compared to conventional reference systems	Bennion et al., 2015; Luterbacher et al., 2009

* Denotes a result solely from the discussions in the focus group workshop or from the expert surve

Table 6: Overview of the identified essential barriers for HTP

Category	Barriers	References
Technology		
Feedstock	Several material flows are already in use	Brosowski et al., 2016; Bardt, 2008
	High variation of feedstock composition and quality	Lin et al., 2017; Li et al., 2016
Conversion/ Processing/ Product Composition	Missing reference plants and long-term experiences	*
	Less knowledge on chemical process basics and process efficiency	*
	Missing experiences and knowledge on suitable process water treatment	vom Eyser et al., 2015; Vogel, 2016
Economy		
Costs	Investment uncertainties	*
	No financing security for plant construction	*
	Missing robust cost data for several business cases (esp. large-scale)	*
Sales	No estimations on product potential available	*
	High competition on sales market	*
	Sometimes low product quality	*
Environment		
Environment	High contamination of process water (e.g. COD values to high)	Vogel, 2016; Wirth and Mumme, 2013
	Little knowledge about stability of HTC char in soil as carbon sink	Naisse et al., 2015; van Zwieten et al., 2010

* Denotes a result solely from the discussions in the focus group workshop or from the expert survey

The previous tables show the importance of using expert estimations next to a literature review. In particular, the analysis of the economic aspects is almost completely based on the expert estimations. There was nearly no peer-reviewed literature investigated that is dealing with economic potentials and barriers of HTP.

As previously mentioned, besides these dimensions, also legal aspects are considered as frame-setting conditions. They are especially useful to set threshold for criteria values and make them potentially measurable. For the case of Germany this includes following potentials and barriers.

Legal aspects generating potentials for HTP in Germany:

- Strict legislation for the utilization of sewage sludge for agriculture due to the amendment of the fertilizer ordinance (DüMV) enhances the need for alternative treatment paths like HTP (Libra et al., 2011).
- The new sewage sludge ordinance (AbfKlärV) regulates phosphorous recycling of sewage sludge that exceeds certain phosphorous thresholds, hence the co-incineration

of sludge with high P-values is permitted which is a chance for HTP with integrated P-Recycling as treatment option (Greve et al., 2014).

Legal aspects generating barriers for HTP in Germany:

- HTP products from substrates like sewage sludge are currently not authorized as fuel or fertilizers, they are legally seen as waste which impedes the application for some fields. Fuels from sewage sludge can only be used in waste incineration waste co-incineration plants in accordance with the 17th Federal Emissions Control Act (BImSchV) (Gawel et al., 2015).
- A lack of standards (e.g. product certificates) and norms for HTP products and the processing itself increases uncertainties for stakeholders, especially because they are not comparable to competitive products and processes (Libra et al., 2011).
- Current legal thresholds on the discharge of waste water into public waste water treatment plants aggravates the necessity of suitable solutions for process water treatment (optimally on-site) (Reißmann et al. 2018).

3.2. SWOT analysis and development of strategic targets

Through a SWOT analysis, factors were identified that are unfavorable or favorable for a successful application of HTP as options for the treatment of biogenic residues. Based on this, success strategies/targets can be derived which furthermore were used to develop assessment criteria. Tables 7-9 show the results of the SWOT analysis.

Table 7: SWOT analysis for the development of strategic targets on technological aspects

	Internal Analysis for technological aspects		
External Analysis for technological aspects		**Strengths (S)** (1) High suitability for wet and sludgy residues (2) High energy efficiency of process (3) High energy content and carbon content of end-products	**Weaknesses (W)** (1) Less knowledge on chemical process basics (2) Less experience and knowledge on process water treatment
	Opportunities (O) (1) Integrate phosphorus recycling in process concepts (2) New treatment options for sewage sludge are needed	*SO-targets*$_{tech.}$ • Use available wet and sludgy residues, especially sewage sludge (S1/O2) • Improve material and energy balance of the process and integrate P-recycling (S2/S3/O1)	*WO-targets*$_{tech.}$ • Focus on knowledge building for (chemical) process design with integrated P-recovery (W1/O1) • Focus on knowledge building on process water treatment, especially with sewage sludge as feedstock (W2/O2)
	Threats (T) (1) Several material flows already in use which reduces available feedstock (2) Variation of feedstock composition and quality (3) Missing reference plants and long-term experiences	*ST-targets*$_{tech.}$ • Concentrate on available and best suitable wet and sludgy feedstock (S1/T1/T2)	*WT-targets*$_{tech.}$ • Focus on knowledge building on (chemical) process design and process water treatment for existing plants (W1/W2/O3)

The SWOT analysis for technological aspects shows that strategic targets regarding the availability of the substrates, process water treatment and suitable process design are most important. Especially knowledge building seems essential to improve the potential success of HTP concepts for the management of biogenic residues. Some of the targets could be underpinned with quantitative values if available (see Section 3.3). For example, the target S1/O2 can be quantified through moisture content of the substrate (parameter for "wet and sludgy") or maximum distance to the treatment plant (parameter for "availability").

Table 8: SWOT analysis for the development of strategic targets on economic aspects

		Internal Analysis for economic aspects	
External Analysis for economic aspects		**Strengths (S)** (1) Large product variety	**Weaknesses (W)** (1) No robust data for large-scale business and reference cases (2) Sometimes low product quality (3) No estimations for product potential
	Opportunities (O) (1) Inter- and cross-sectorial cooperation (2) Estimated decrease in production costs for HTP	*SO-targets*$_{econ.}$ • Focus on products with highest estimated decrease in production costs (S1/O2)	*WO-targets*$_{econ.}$ • Use cooperation to generate and share data for business cases (W1/O1) • Focus on products with high quality and high estimated decrease in production costs (W2/O2) • Estimate product potential and integrate estimated decrease in production costs (W3/O2)
	Threats (T) (1) Investment uncertainties and missing financial security (2) High competitive situation	*ST-targets*$_{econ.}$ • Focus on product markets with relative low competitive situation (e.g. find niche) (S1/T2)	*WT-targets*$_{econ.}$ • Estimate product potential and generate data for business cases to reduce investment uncertainties (W1/W3/T2)

Economic targets concentrate on production costs, product potential and product quality as well as data availability for business cases. Some of these targets seem to be easy to connect with a criterion, e.g. production costs which is already an economic assessment criterion. Other criteria seem to be more complicated to asses, such as data availability on business cases. Usually, such aspects will not be addressed through economic evaluation criteria. Through the applied method also these kinds of issues will be connected to criteria which shows the added value of this structured approach. Also for the economic targets, some of the corresponding criteria should be quantifiable, e.g. production costs.

Table 9: SWOT analysis for the development of strategic targets on environmental aspects

	Internal Analysis for environmental aspects		
External Analysis for ecological aspects		**Strengths (S)** (1) Low Global Warming Potential (GWP)	**Weaknesses (W)** (1) High contaminated process water
	Opportunities (O) (1) HTC char as carbon sink	*SO-targets*$_{env.}$ • Focus on the potential of GWP (CO2) reduction via HT processes and products (S1/O1)	*WO-targets*$_{env.}$ • Ensure a high carbon transfer into the end-product to reduce process water contamination and foster quality of end-product (W1/O1)
	Threats (T) (1) Unknown stability of HTC char in soil	*ST-targets*$_{env.}$ • Concentrate on greenhouse gas reduction potential through processing (S1/T1)	*WT-targets*$_{env.}$ • Focus on the suitable and ecological treatment of by-products and avoid negative environmental effects due to knowledge gaps (W1/T1)

Environmental targets refer especially to the GWP of HTP and resulting products as well as the environmentally friendly treatment of by-products like the contaminated process water. Especially the development of criteria for the environmentally friendly process water treatment will be new and innovative because most reference processes to HTP (e.g. pyrolysis) are not confronted with such contaminated liquid by-products. Hence, no criteria can be easily adopted from comparable technology assessments.

3.3. Development of assessment criteria

Based on Table 4 and the explanations made for steps 5 and 6 of the methodology section, the general criteria were connected to the SWOT targets. The chosen general criteria were modified to fit the HTP targets. Generally, sub-criteria were preferred because they are more specific than main criteria. Just for the case that the target fits to several sub-criteria of a main criterion the main criterion was chosen. Figures 4-6 show the arrow/process diagrams for the connection of strategic targets and criteria as well as the derived modified criteria for the HTP evaluation.

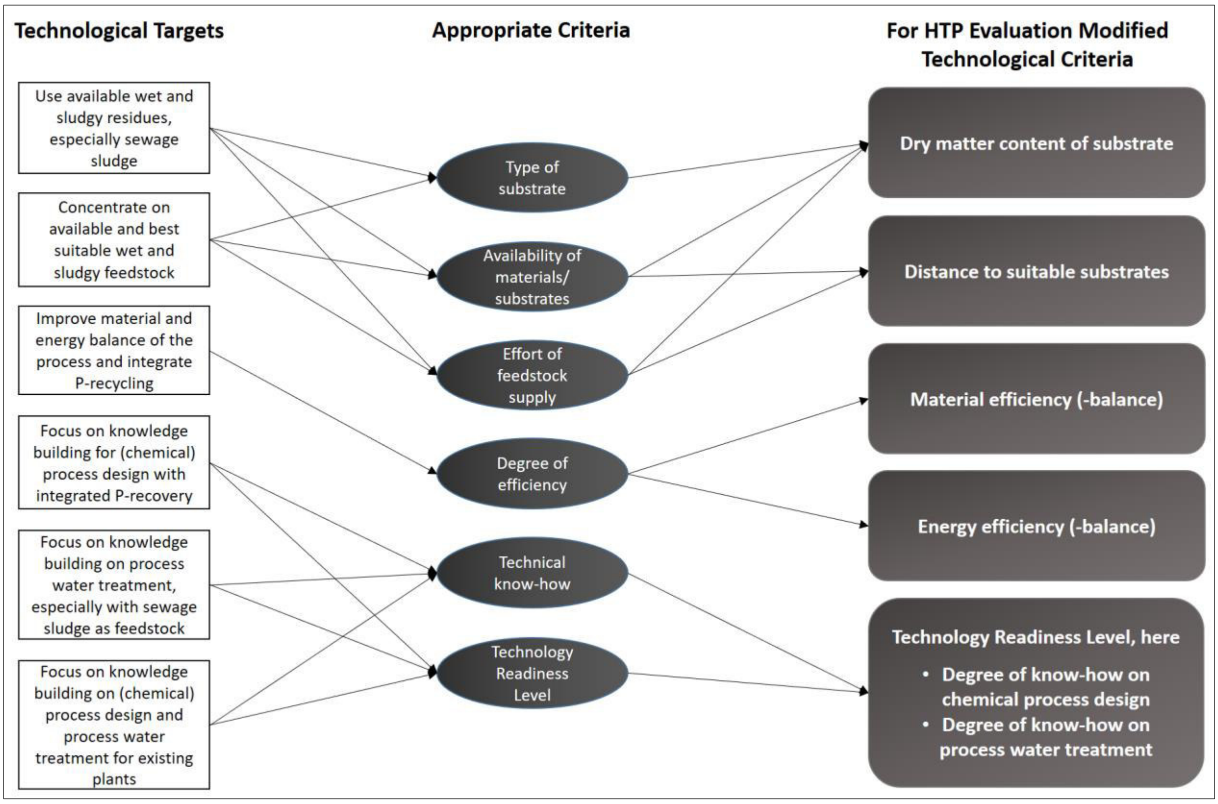

Figure 4: Process diagram for the derivation of technological criteria

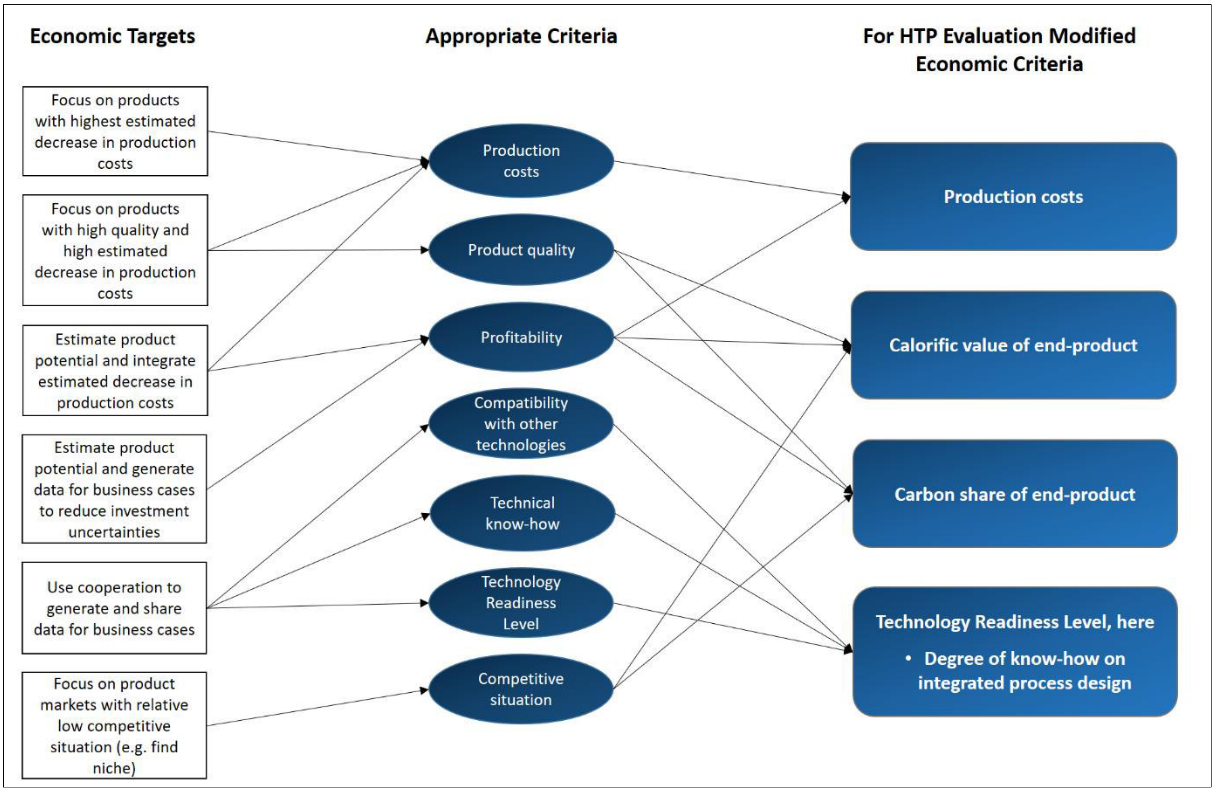

Figure 5: Process diagram for the derivation of economic criteria

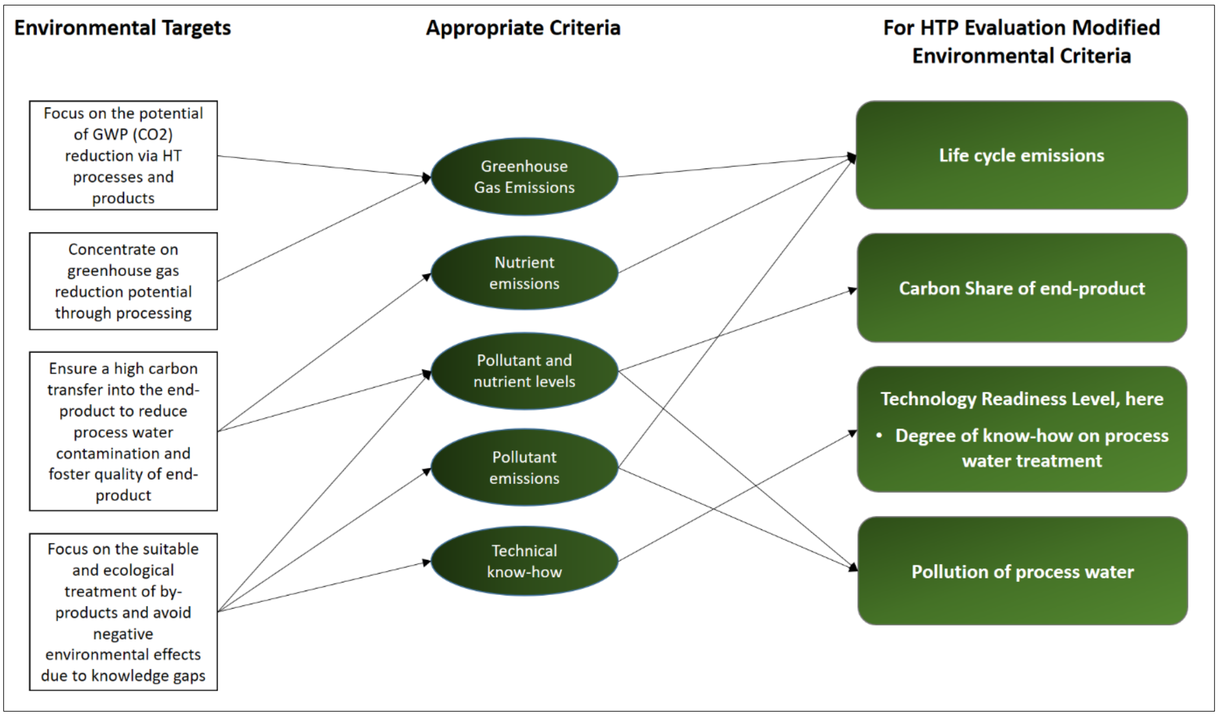

Figure 6: Process diagram for the derivation of environmental criteria

Because the importance of integrated phosphorus recycling during the processes was mentioned multiple, an additional criterion named "*recycled phosphorus*" is introduced.

The relevant criteria to assess the potential for HTP as options for the treatment of biogenic residues as well as their measurement units are presented in Table 10 as summarizing overview. It is differentiated between input and output metrics. Input metrics represent criteria that must be minimized, whereas output metrics represent criteria that should be maximized to enhance efficiency. The dry matter content of the substrates represents a K.O. criterion because a specific range is necessary for HTP to become a suitable treatment option.

Table 10: Identified criteria for evaluating HTP as options for the management of biogenic residues including measurement scales & units and target values/ranges

Criteria	Definition	Unit	Relevant process step	Number of targets addressed
Dry matter content of substrates	The relation of organic dry matter to water content of the substrate. Recent studies recommend an organic dry matter content between 10 to 30 % for optimal processing. If this range is not fulfilled the considered substrate is not suitable and hence the alternative may be excluded from the analysis (Reißmann et al. 2018a).	Percent of organic dry matter content	Feedstock provision	2
Production costs	Raw material costs and manufacturing costs of the product (e.g. hydro-coal) (Bronner 2013).	Euro per functional unit	Feedstock provision and conversion/ refinement	4
Distance to suitable substrates	Transport distance of suitable substrates from place of occurrence to treatment plant.	Kilometer (km)	Feedstock provision	2
Pollution of process water	Share of organic substances in residual water that occurs after hydrothermal processing (Fettig et al. 2015).	mgO_2/L (COD value)	By-products	2
Life cycle emissions	Pollutant emissions occurring through the process steps relating to the system boundaries (ISO 2006).	Global Warming Potential (CO_2 equivalent)	All process steps	2
Output metrics				
Technology Readiness Level	Classification of the level of development of a considered technology according to ISO 16290 (ISO 2013).	Assessed on a scale from 1 to 9 (cf. Mankins, 1995)	All process steps	6
Material efficiency (-balance)	Relation of product output to raw material input (Eichhorn 2000).	Percent of functional unit	Conversion/ refinement	1
Energy efficiency (-balance)	Relation of energy output to energy input (Eichhorn 2000).	Percent of functional unit	Conversion/ refinement	1
Calorific value of product	Maximum usable heat amount through the combustion of the end-product (coal, oil or gas) (Brandt 2004).	Mega Joule (MJ) per functional unit	Product Usage	4
Carbon share of end-product	Share of carbon in HTC coal in relation to total mass volume.	Percent	Product Usage	4

Share of recycled phosphorus	Share of phosphorus that is recycled in relation to the total substrate feed-in.	Percent	Recycling	2

4. Discussion

By connecting the general criteria from technology and sustainably assessment with the targets derived from the SWOT analysis (Figure 4-6) it becomes possible to select specific criteria which reflects technology specific potentials and barriers for the chosen dimensions. Because the relevant information was identified with an expert survey, workshop and literature review the criteria are objective and transparent.

Considering the number of mentioned potentials and barriers and the derived SWOT targets a focus is set on criteria for the technological dimension. Especially the TRL seems to be an essential assessment criterion, which shows the high number of addressed targets. Based on the identified criteria of this analysis, a next step will be to prove the availability and quality of needed data and check the independency of the criteria to each other for specific cases (see step 7 of the methodology).

Most selected criteria are measurable on a cardinal scale. Just the TRL assessment depends on an ordinal scale, which means that the measured elements can be ranked but no quantifiable differences between these ranks can be measured (David and Nagaraja, 2003). This is of importance for the selection of a suitable assessment method because for some methods scales must be adapted if attributes depend on an ordinal scale (cf. Peters and Zelewski, 2007). Only for the moisture content of the substrate, a target range exist which is why this criterion has been identified as a K.O. criterion. For this reason the range must be fulfilled to ensure an economic processing (Vogel, 2016; Greve et al., 2014).

From a methodological point of view, it can be determined that instruments from strategy development seem suitable for a structured development of evaluation and assessment criteria of technologies, if the overall target – in this case the technologies suitability for the treatment of biogenic residues – is clearly specified. Hence, the introduced method is also transferable for other contexts of criteria development. The most critical step for a successful criteria development is the collection of information. We recommend to integrate estimations of relevant experts next to a general literature investigation. In this analysis, many potentials and barriers have been identified based solely on expert estimations.

Regarding the goal of this work, it was shown how this approach can be used to develop technology specific assessment criteria for different evaluation dimensions. A central advantage of this method is the high transparency levels of the resulting criteria, which can be ensured through the integration of several independent experts.

A shortcoming is the relative high effort for the information collection procedure. However, especially for new and emerging technologies this effort will be very worthwhile because the information can be also used for additional purposes than criteria development, e.g. strategy development or qualitative technology forecasting. Mostly, SWOT analysis are common practice for companies and other entities. Hence, the application of this structured approach will be easy to integrate because a well-known instrument (SWOT analysis) can be used.

5. Conclusion

This analysis was carried out to present a transparent and structured approach for developing dedicated criteria to assess the suitability of HTP for treating biogenic residues. With the approach explained in section 2 it became possible to derive such criteria by using elements from strategy development, in particular SWOT analysis. The general approach can be used for different cases of criteria development unless that this study was focusing on HTP. In result, the most important assessment criteria seem to be the TRL, production costs and the carbon share and calorific value of the end-product. However, it should be considered that a slight tendency for the selection of criteria is connected with the selection of the expert panel. In this case, technology oriented stakeholder groups dominated which is a possible reason for the high importance of the criterion TRL. This is why it is recommendable to create an expert panel that represents mostly all stakeholders in a balanced way.

In many of the discussions carried out with experts in the field, one subject that prompted was the development of a tool based on multi-criteria analysis to transmit these criteria into a robust, transparent and holistic methodological framework. Such an instrument needs to be developed and tested for case studies to validate the applicability. The value-added of the instrument will be that the technologies of the HTP platform (HTC, HTL, HTG) will become comparable to each other and to specific reference systems (e.g. pyrolysis). Next to this, the assessment procedure will be able to compare the generic platform types based on average data as well as specific concepts based on real data from practice. It can be used by different stakeholder groups, e.g. for investment or funding decisions. Further studies will focus on developing such an assessment instrument or instruments to support future decisions in this field of technology. In particular, the use of such a multi-criteria analysis tool for assessing scenarios - that represent potential future pathways of HTP - will be an essential part of forthcoming studies.

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