How to identify suitable ways for the hydrothermal treatment of wet bio-waste? A critical review and methods proposal

Reißmann, Daniel [a,*], Thrän, Daniela [a, b], Bezama, Alberto [a]

[a] Department of Bioenergy. Helmholtz-Centre for Environmental Research – UFZ. Permoserstraße 15, 04318 Leipzig, Germany

[b] Deutsches Biomasseforschungszentrum gemeinnützige GmbH. Torgauer Straße 116, 04347 Leipzig, Germany

* Corresponding author: daniel.reissmann@ufz.de

Abstract

A considerable amount of wet biogenic residues and waste has no resource-efficient use in several European countries yet. Hydrothermal processes (HTP) seem to be promising for treating such biomass as they best work with substrates with 70% to 90% water content. However, thus far the suitability of HTP for this purpose has not been sufficiently evaluated, for which this work aims to identify suitable multi-criteria analysis (MCA) methods that can be used to identify promising ways for the hydrothermal treatment of wet bio-waste. A review on 31 recent MCA studies in (bio-) waste management was conducted with the aim of comparing them to methodological requirements for evaluating HTP. Furthermore, a MCA approach for HTP based on the review findings is proposed. Results show that no observed MCA method is directly transferable for assessing HTP, for which a customized approach combining the Analytical Hierarchy Process and the Technique for Order Preference by Similarity to Ideal Solutions is proposed and preliminarily validated with literature data. These preliminary calculations indicate that hydrothermal gasification seems most promising under consideration of multiple criteria using the available average and exemplary data. However, needless to say there is still a long way to go to obtain the sufficient adequate data to validate and use appropriately the model, for which further studies are necessary to acquire more reliable data and to assess also future technology developments of HTP.

Keywords: review; Hydrothermal Processes; biogenic waste; multi-criteria analysis; Analytical Hierarchy Process; Technique for Order Preference by Similarity to Ideal Solution

List of abbreviations:

AD	**Anaerobic Digestion**
AHP	Analytical Hierarchy Process
DEMATEL	Decision-Making Trial and Evaluation Laboratory
EURct	Euro cent
$gCO_2eq.$	Grams of carbon-dioxide equivalent
HTC	Hydrothermal Carbonization
HTG	Hydrothermal Gasification
HTL	Hydrothermal Liquefaction
HTP	Hydrothermal Processes
kg	Kilogram
kWh	Kilowatt hour
MCA	Multi-criteria analysis
MJ	Megajoule
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
QFD	Quality Function Deployment
SI	Supplementary Information
TA	Technology Assessment
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
VIKOR	Vise Kriterijumska Optimizacija I Kompromisno Resenje

Introduction

The efficient use of biogenic residues and waste can reduce costs and greenhouse gas emissions, save natural resources and promote climate protection (BMWi 2015). Besides, such a utilization can foster the progress towards a bio-economy (cf. BMEL 2014, European Commission 2012) that aims a value-added treatment of biomass for producing materials, chemicals, fuels and energy in a sustainable manner and after providing sufficient food and feed for societal needs (Bezama 2016, Thrän & Bezama 2017). However, a considerable part of biogenic residues and waste is inefficiently (e.g. energetic use despite of low heating values) or not even used yet (cf. Brosowski et al. 2016, Pehlken et al. 2016, Tröger et al. 2013). A study that analysed twelve countries of the European Union focusing on the potential of biogenic residues for cellulosic biofuel production has shown that particularly France has high unused amounts of up to 60 million metric tons dry matter per year. Forecasts for 2020 and 2030 even show that these quantities will increase for most of the observed countries (Searle & Malins 2015). Considering this, the identification of suitable technological solutions for sustainably utilizing such bio-waste in future is of high interest for research and practice (cf. BMWi 2015, Tröger et al. 2013, Parawira et al. 2008). Previously, it was determined that especially the treatment of wet and sludgy substrates has gained rising attention in the last years (Reißmann et al. 2018). In contrast to solid bio-waste, wet and sludgy residues need an energy-intensive and cost-intensive pre-treatment (e.g. drying, thickening) to be suitable for conventional biomass treatment paths which impedes their usage. However, some biomass conversion processes are generally applicable to treat these residual streams (Zhang et al. 2014). For example, biochemical processes like AD and thermo-chemical processes like pyrolysis (Poulsen et al. 2012, Han et al. 2016, Wzorek & Tańczuk 2015). Nonetheless, shortcomings are connected to the mentioned treatment paths which impede the decision for the optimal solution (e.g. difficulties due to high pollutant/nutrient contents) (Rulkens 2008, Saxena et al. 2009, Nielfa et al. 2015, Prabhu & Mutnuri 2016). Besides, while most biomass with a high moisture content were treated via AD for energetic purposes in the past, requirements of the European Waste Framework Directive prior a material treatment before an energetic use since 2008 (European Union 2008). Thus, processes that include material fields of application are of certain interest. Due to these obstacles and requirements, substantial amounts of wet biogenic residues are not in use yet or will need new ways of treatment in future. Activities in research and practice indicate that HTP seem to be promising paths for transforming wet biomass into gaseous, liquid or solid carbon containing products by thermochemical conversion (Hallesche Stadt und Wasserwirtschaft 2015, Kruse et al. 2013, Libra et al. 2011, Lin et al. 2017). The procedure needs high water containing substrates for optimal processing, which is why materials like sewage sludge are particularly suitable (Greve et al. 2014). Depending on the process parameters (temperature, pressure and residence time) different HTP types occur (Tab. 1).

Table 1. Overview of HTP types (adapted from Reißmann et al. 2018)

HTP type	Brief definition	Process characteristics
HTC	Coalification process converting biogenic materials into hydro-char (Fiori & Lucian 2017). Hydro-char is primary used for energetic purposes, material applications and in agriculture as fertilizer or soil conditioner (Lu et al. 2012).	160 – 250 °C
		10 – 30 bar
		1 – 72 hours
HTL	Process transforming biogenic materials into chemicals and bio-oil (Zhang 2010). Bio-oil is used as liquid fuel for energy production and as substitute to crude oil for cosmetics and chemical industry (Kruse et al. 2013).	180 – 400 °C
		40 – 200 bar
		10 – 240 minutes
HTG	Process converting biomass into gaseous materials, primary methane and hydrogen. The main products are used for energetic purposes and for applications in the chemical industry (Kruse 2009).	350 – 500 °C
		230 – 400 bar
		< 10 minutes

The suitability for the hydrothermal treatment of wet bio-waste has not been sufficient evaluated yet. Hence, there is a particular interest for a tailor-made assessment approach (cf. Reißmann et al. 2018, p. 248). A stakeholder workshop carried out in September 2016 in Leipzig (cf. DBFZ 2016) showed the need of an assessment tool considering multiple attributes. Most stakeholders argued that the assessment of HTP by multiple criteria will help to reduce uncertainty for decision-making regarding funding and investment but also to identify research priorities for HTP. However, most current studies concentrate on single aspects like optimization of process parameters (cf. Aggrey et al. 2012, Elliot 2008, Klingler & Vogler 2010), economic assessment (cf.

U.S. Department of Energy 2016, U.S. Department of Energy 2014) or life cycle assessment (cf. Ahamed et al. 2016, Bennion et al. 2015). But to recommend promising technology development paths based on scenarios (e.g. increase of full-scale HTP plants in Europe due to implementation of cost-effective treatment for process water), a suitable multi-criteria assessment tool indicating if HTP are still promising based on computations with data on economic, environmental and technological aspects seems useful. Thus, the question that rises is how it will be possible to identify most suitable ways for the hydrothermal treatment of wet bio-waste by considering multiple attributes.

This study wants to contribute to the solution of this question. Therefore, the goals of this work are: Providing an overview of MCA methods commonly used in (bio-)waste management research, defining necessary requirements to evaluate HTP in a systematic way, analysing if common used MCA methods fulfil these requirements and *if not* proposing a MCA approach to evaluate HTP for managing wet biogenic residues that fulfils all requirements.

Materials and methods

The work was organized in three steps as presented in Table 2.

Table 2. Methodological sequence of the study

Steps	Aims	Methods

1 Review	Identification of most common MCA methods in waste management and bio-waste management.	Search strategy based review.
2 Applicability check	Proofing applicability of MCA methods for evaluating HTP.	Checklist with methodological requirements for HTP assessment.
3 Methods development	Proposing a tailor-made MCA procedure for HTP. Preliminarily validation of the proposed approach with data from literature.	Adaption and/or combination of MCA methods within an assessment approach fulfilling the methodological requirements.

Step 1: Review

A literature review was executed to identify most common used MCA methods in (bio-)waste management research by applying a structured search strategy (Tab. 3).

Table 3. Search strategy

Category	**Specification**	**Reason for specification**
Considered time period	Sources not older than five years.	Only most recent MCA methods should be identified.
Considered sources	Google, Google Scholar, Scopus, Science Direct.	Most common search engines for scientific purposes.
Considered document types	Scientific articles, conference proceedings, books and book chapters.	Most common document types for publishing scientific analysis.

Search terms	Multi-criteria analysis waste management; multi-criteria analysis bio-waste management; multi-criteria decision-making waste management.	Search terms were defined with respect to the aim of step 1.

About 90 studies were identified. However, documents had to be excluded due to missing details regarding the used MCA methods and an insufficient focus on (bio-)waste management contexts. After all, 31 documents were reviewed with regard to the used MCA methods.

Step 2: Applicability check

The suitability of the identified methods is proofed by using a checklist on methodological requirements. For this, a point scale is used to assess the level of suitability, i.e. 2 points mean that the requirement is fulfilled, 1 point means that the requirement is in part fulfilled and 0 points mean that the requirement is not fulfilled.

Step 3: Methods development

If no considered MCA method fulfils all requirements, this means that no method is directly transferable for evaluating HTP. Hence, a tailor-made approach for HTP will be proposed. For this, most suitable MCA methods will be combined and/or adapted in an overall TA procedure.

Results and Discussion

Review on multi-criteria assessment studies in (bio-)waste management

31 studies were analysed of which four are review articles. Table 4 shows the thematic focus and applied MCA methods of the observed studies.

Table 4. Thematic focus and MCA methods of observed studies

Thematic focus	Applied MCA method	Corresponding studies	Additional information
General focus	AHP	Milutinović et al. (2017)	-
		Achilles et al. (2013)	79 articles reviewed by this study
	Fuzzy AHP	Zare et al. (2016)	-
	PROMETHEE	Makan et al. (2013)	-
	VIKOR	Opricovic & Miloradov (2016)	-
Municipal solid waste	AHP	Milutinović et al. (2014)	-
		Antonopoulos et al. (2014)	-
		Soltani et al. (2015)	68 articles reviewed by this study
		Thampi & Rao (2014)	-
		Vučijak et al. (2016)	-
	TOPSIS	Nouri et al. (2014)	-
		Jovanovic et al. (2016)	-
		Klavenieks et al. (2017)	-

		Asefi & Lim (2017)	-
	PROMETHEE	Panagiotidou et al. (2015)	-
	QFD	Santos et al. (2017)	-
	Combined method	Herva & Roca (2013)	Combination of AHP and PROMETHEE
Industrial waste	AHP	Nouri et al. (2018)	-
		Coelho et al. (2017)	260 articles reviewed by this study
	Combined method	Mir et al. (2016)	Combination of TOPSIS and VIKOR
		Chauhan & Singh (2016)	Combination of fuzzy AHP and fuzzy TOPSIS
Healthcare waste	AHP	Yap & Nixon (2015)	-
		Mardani et al. (2015)	393 articles reviewed by this study
	Fuzzy VIKOR	Liu et al. (2013)	-
	Combined method	Hariz et al. (2017)	Combination of AHP, VIKOR and PROMETHEE
Waste management issues	VIKOR	Liu et al. (2014)	-
	AHP	Ferreira et al. (2015)	-
		Majumdar et al. (2017)	-
	Fuzzy DEMATEL	Wang et al. (2018)	-
	Combined method	Arıkan et al. (2017)	Combination

			of fuzzy TOPSIS and PROMETHEE
		Shahba et al. (2017)	Combination of AHP and TOPSIS

None of the assessed studies is focusing on bio-waste management which indicates the lack of MCA approaches for this field of study. In contrast, 39% of the studies focus on municipal solid waste management. Thus, in most studies bio-waste is at least partly regarded as it is a fraction of municipal solid waste. However, the management of wet and sludgy biogenic residues is not considered by the observed studies. For healthcare waste (13%), industrial waste (13%) and management issues (19%) like site selection, waste collection and paper waste management MCA methods are applied too. The review results show once more the necessity of a customized MCA approach for HTP, because even no appropriate MCA approaches exist for relative fields like the assessment of technologies for the management of wet bio-waste in general.

Table 5. Descriptions of the MCA methods used by the observed studies

MCA method	**Description**	**Reference**
AHP	Identification of preferences by pair-wise comparisons of criteria using a procedural sequence. Criteria are sorted hierarchical.	Saaty, 1987
DEMATEL	Analysing and solving complex and intertwined problems by verifying interdependence between variables. Improving them by creating a specific chart to reflect interrelationships between	Fontela and Gabus, 1976

	variables.	
PROMETHEE	Multi criteria decision making by building of an outranking between different alternatives.	Brans et al., 1986
QFD	Several quality criteria are combined within a QFD matrix to show correlations. Aim is to identify products and services that are desired by customers under consideration of multiple criteria.	Akao, 1992
TOPSIS	The advantageousness of an alternative is assessed by determining the distance to the (virtual) best and worst alternative.	Hwang & Yoon, 1981
VIKOR	Multi-criteria optimization of complex systems based on ranking and selecting from a set of alternatives considering conflicting criteria. The ranking is performed by comparing the measure of closeness to the ideal alternative.	Opricovic, 1998
Fuzzy logic MCA	MCA that deal with unclear information (fuzziness). Through fuzzy logic it is possible to precise unclear descriptions of criteria such as “good” or “bad”. In general, all of the above-mentioned MCA can be enlarged with fuzzy logic.	Abdullah, 2013
Combined methods	The MCA combine two or more of the above-mentioned methods within a common technology assessment procedure.	-

Most studies use the AHP (42%) which is also confirmed by the observed review articles (cf. Coelho et al. 2017, Soltani et al. 2015, Mardani et al. 2015, Achillas et al. 2013). However, also combined methods are applied by 23% of the studies. Table 5 describes the considered methods and combinations/adaptions briefly.

Because none of the considered MCA is focusing on bio-waste management, this analysis will provide novel information on the suitability of MCA methods for bio-waste management especially for the hydrothermal processing of wet biogenic materials.

Applicability check of identified MCA methods

To check the applicability of the identified MCA methods for evaluating HTP, methodological requirements must be defined. General requirements are transparency, consistency and transferability (cf. Billig 2016, DFG 2013, Ganzevles & van Est 2012, Scheffzcik 2003). Besides, the following aspects have to be fulfilled by a suitable method for evaluating HTP.

Holistic nature: Thermo-chemical and bio-chemical biomass conversion technologies and energetic as well as material treatment paths can be considered.

Multi-dimensionality: Quantitative and qualitative techno-economic and environmental attributes can be considered simultaneously.

Applicability: The method is easy to apply also without detailed background knowledge (e.g. for calculations).

Objectivity: The selection and weighting of criteria involves stakeholder/experts to ensure transparency, relevance and objectivity of criteria.

Adaptability: The procedure is iterative, to make steps repeatable and adaptable.

Benchmarking: Target values considering certain requirements can be determined.

The identified MCA methods were checked with regard to the mentioned requirements (Tab. 6). Fuzzy logic MCA and combined methods were not considered as they do not represent own MCA methods but adaptions, extensions and combinations of them. As mentioned, a point scale from 0 to 2 was used to assess the MCA methods regarding requirement fulfilment. Details for the rating are described in the SI section.

Table 6. Comparison of MCA methods regarding requirement fulfilment

	AHP	DEMATEL	PROMETHEE	QDF	TOPSIS	VIKOR
Holistic nature	2	2	2	1	2	2
Multi dimensionality	1	2	1	2	1	1
Applicability	2	1	2	1	2	1
Objectivity	1	0	1	1	1	1
Adaptability	2	1	2	1	2	2
Benchmarking	1	0	1	0	1	1
Degree of Fulfilment (absolute)	9/12	6/12	9/12	6/12	9/12	8/12
Degree of Fulfilment (relative)	75 %	50 %	75 %	50 %	75 %	66 %

Results show that no identified MCA method fulfils all requirements and is therefore directly applicable to HTP evaluation. Thus, a combined method including most useful elements of the considered MCA approaches must be developed to reach a higher degree of fulfilment. AHP, PROMETHEE and TOPSIS seem most suitable because they already reach high degrees of fulfilment. They fulfil the requirements holistic nature, applicability and adaptability. The requirement multi-dimensionality is in part fulfilled through these methods. Qualitative criteria are considered if they are measurable on an ordinal scale (i.e. a scale with similar distances). Hence, nominal values (e.g. “yes” or “no” attributes) cannot be considered by the methods. However, most criteria values are at least ordinal. Regarding the requirement objectivity, the AHP seems more suitable because expert involvement is usually part of the criteria weighting. Further, a criteria selection or weighting procedure is not part of PROMETHEE and TOPSIS at all. Hence, for criteria weighting the AHP should be used. However, for determining criteria, AHP, PROMETHEE and TOPSIS include no expert involvement. This is why an own approach for a more objective criteria determination was previously developed. Regarding benchmarking, AHP, PROMETHEE and TOPSIS can be enlarged with a sensitivity analysis to determine potential thresholds or to test scenarios. Thus, the aimed method should also include a sensitivity analysis. Especially, because of its higher applicability and the more intuitive interpretability of the results compared to the AHP and PROMETHEE, TOPSIS will be used for the comparison of alternatives.

Proposed MCA procedure for evaluating HTP

Previous results indicate the lack on sufficiently suitable MCA methods for HTP assessment which is why a tailor-made procedure is proposed. This method will assess HTP to each other and relevant reference systems by considering multiple attributes for the first time. The following step-wise and iterative procedure was developed. Because the basic procedure is structured as a TA framework, the approach is in part transferable to comparable evaluations of biomass conversion processes.

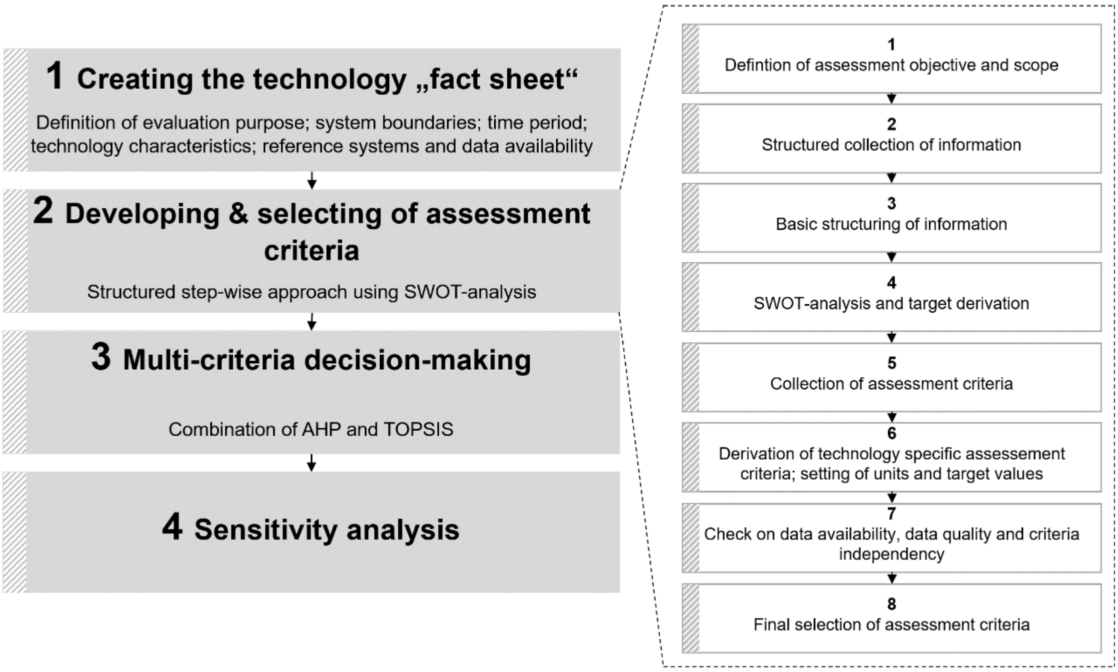

Figure 1. Methodological sequence of MCA approach for assessing HTP

The technology "fact sheet": Setting the investigation framework and describing the considered technologies

To get consistent, interpretable and transparent results, first it is necessary to set an investigation framework which defines evaluation purpose, system boundaries and considered time period. Further, most important technology characteristics must be described to enhance the transparency and thus the interpretability of the results. After, the system boundaries of the considered technologies must be set. The system can contain (1) feedstock provision & pre-treatment, (2) conversion & refinement, (3) products & by-products, (4) logistics & distribution, (5) product usage & (6) deposition or re-use/recycling (end-of-life). This is especially important to define suitable reference systems, e.g. if no products are considered, reference systems must not necessarily operate on competitive product markets. Often it is not needed to consider all system components because of an already specific assessment purpose. In addition, the decision for including system components depends on data availability, which is why system boundaries are often limited. It is crucial to check data availability on system components and set them in context to the necessity of including them. Several TA studies recommend that effort and benefits of the analysis must be in balance to ensure the applicability (cf. Billig & Thrän 2017, Billig & Thrän 2016, Hall 2012). After defining the system boundaries, suitable reference systems must be determined to enhance the interpretability of results. For HTP, the determined reference systems should be competitors for the same substrates that could be utilized through HTP and/or operate at the same product markets. Depending on the analysis focus the general TA procedure can be adopted at this point (e.g. if specific conversion efficiencies are compared). However, the definition of reference systems depends on the assessment purpose and must consider the investigation framework, technology characteristics and system boundaries. In general, the comparability of the considered technologies must be carefully checked at this point. The results of this step can be summarized in a technology "fact sheet" (cf. SI).

Developing and selecting technology-specific assessment criteria

Suitable assessment criteria are crucial to ensure significant results. Criteria must fulfil requirements like objectivity, consistency, adaptability, transparency and non-redundancy. Also, reliable data should be available. The criteria shall represent the assessment object nearly in complete (Rohweder et al. 2015) and should have minimal influence to each other. However, a total independency cannot be reached in practice (Billig 2016). The development of metrics for MCA is usually carried out in a less structured way and through a limited number of primary internal experts (e.g. project team members). Although some guidelines and examples recommend selection factors which can be used, the integration of relevant stakeholder into criteria development is often limited to criteria prioritization (cf. Valenzuela-Venegas 2016, Akadiri & Olomolaiye 2012, Akadiri et al. 2013). To foster objectivity and transparency of criteria derivation, the authors recommend a structured process using instruments from strategy development for the transparent selection of dedicated assessment criteria (cf. Fig. 1, step 2). The derived criteria can be seen as “long list”. This means, depending on the specifications in the “fact sheet”, only a part of the criteria will be used for the actual assessment. It is recommendable to use a decision chart for the final selection of criteria which depends on the analysis case. Finally, only a selection of criteria from the “long list” are taken into account for the analysis.

Multi-criteria decision-making and sensitivity analysis

To weight the selected criteria the AHP will be used. The basic procedure includes the following steps according to Saaty (1990): Creating the decision hierarchy, making pair-wise comparisons of decision-making parameters (criteria and alternatives), calculating priorities of decision-making parameters and check consistency. For the proposed procedure, an adapted AHP is used. This means, only the second and third step is executed. The first step is skipped, because the decision hierarchy is created through the previous steps of the overall procedure and evaluation criteria are already selected. The comparison of alternatives is part of TOPSIS and thus also excluded at this point. Thus, the AHP is primary applied for derivation of criteria weightings. It is recommendable to use expert estimations to generate the weightings. For this, pair-wise comparisons of all criteria c_i to each other have to be carried out. To select the expert estimations a Delphi survey can be applied. The Delphi method is a systematic survey scheme with multiple steps containing feedback loops. The aim of this method is to reduce misjudgements of experts by applying the survey at least two times (Rowe & Wright 1999).

After executing the AHP, the consistency of the weightings has to be checked. This means, if the criteria are ranked like A > B > C than also A > C must be valid (Saaty 1987). However, this form of consistency is often not fulfilled if several criteria and criteria relations are part of the analysis. For this, Saaty (1987) has developed the Consistency Index (*C.I.*) and the Consistency Ratio (*C.R.*) which can be calculated with

AHP software by using the maximum eigenvalue (λ_{max}) of the corresponding eigenvector. The following equation (eq. 1) must be used:

$$C.I. = \frac{\lambda_{max} - n_z}{n_z - 1} \qquad (1)$$

$$C.R. = \frac{C.I.}{R.I.} \text{ with } C.R. < 0.1 \text{ to ensure consistency.}$$

R.I. means Random Index which is an average Consistency Index of randomly reciprocal matrices. The *R.I.* is given by Saaty (1987) with regard to the number of criteria.

The weighted criteria are furthermore used in TOPSIS. In TOPSIS, a set of different decision alternatives are compared in relation to each other by using multiple criteria and taking the best-case and worst-case as benchmarks (Hwang & Yoon 1981). Thus, the best alternative in relation to other ones that are part of the analysis is calculated. This is why these types of MCA are also named multi-attribute decision-making with a discrete solution space (Geldermann & Lerche 2014). The more alternatives and criteria are applied the significance of TOPSIS' results rises accordingly. However, also the effort for the application of this method rises with a higher number of alternatives and criteria which is why a useful balance between significance and effort must be considered regarding the assessment objectives. In comparison to classical MCA methods like utility analysis, TOPSIS is able to handle a high number of criteria if preferences are not fully clear. Thus, this assumption of TOPSIS adequately represents reality and needs less information from the decision maker (Geldermann & Lerche 2014). Further, TOPSIS needs just the criteria weightings as input from the decision maker which is why the procedure is relatively easy to apply in practice. TOPSIS is carried out according to Hwang & Yoon (1981). After calculating the efficiency values c_i, the criteria values and/or the criteria weightings can be varied to show the sensitivity of these parameter on the results (ceteris paribus). Thus, thresholds and benchmarks can be calculated that indicate which values are optimal to reach the best-case frontier for a certain alternative. By creating scenarios that determine specific values for the future also the effects of this on the efficiency of the considered alternative can be shown by adapting the parameter in TOPSIS.

Preliminary method validation

To check the applicability of the procedure a preliminary method validation was executed. Because a large data survey was not carried out so far, the authors use average data on HTP archetypes identified by a literature review (cf. Reißmann et al. 2018, KIC InnoEnergy 2015, Klemm et al. 2009, Stafford et al. 2017). It has to be mentioned that this preliminary calculation was just carried out to validate the model and the results are not reliable so far. Especially, the comparability of calculations made for data on production costs or life cycle emissions need to be carefully proven for all considered technologies. For this exemplary case, such an extensive proofing was not carried out which is why the first results are not scientifically reliable yet. For the criteria weighting an expert survey has to be carried out. Currently, the survey is not finished which is why "estimated" weightings have to be used for this validation. The estimated weightings result from literature information (cf. Reißmann et al. 2018) and first expert estimations made during a workshop in September 2016 in Leipzig (Germany) (cf. DBFZ 2016).

First, the technology fact sheet was created for the observed HTP archetypes and the corresponding reference system (see SI). Second, relevant criteria ("long-list") were derived through the approach described in section 3.3.2 (see SI). This "long-list" was further concentrated on suitable criteria using the illustrated decision chart (Fig. 3).

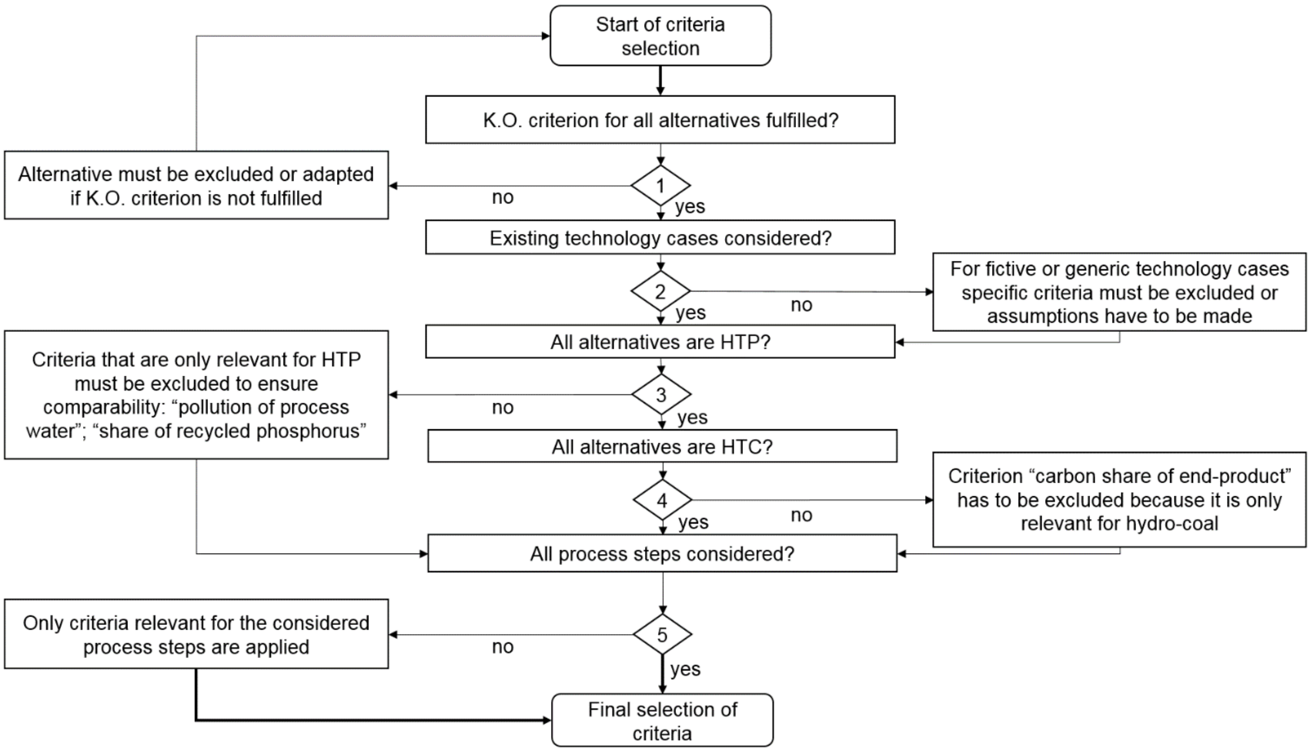

Figure 2. Decision chart for preliminary method application

The resulting criteria and their corresponding weightings are shown in Table 7.

Table 7. Selected criteria for preliminary method application

Criteria	**Unit**	**Weighting**	
Production costs	EURct/kWh	20 %	Inputs
Life cycle emissions	gCO2eq./$MJ_{product}$	18,5 %	
Technology Readiness Level	-	40 %	Outputs
Material efficiency	% kg	7,5 %	
Energy efficiency	% MJ	9 %	
Calorific value of	MJ/kg dry matter	5 %	

end-product			

By using these criteria in TOPSIS for data of HTC, HTL, HTG and AD archetypes, following values for the relative distances c_i result. The data are part of the SI.

Rank 1: HTG - c_i-value of 0.66

Rank 2: AD - c_i-value of 0.48

Rank 3: HTC - c_i-value of 0.32

Rank 4: HTL - c_i-value of 0.26

The exemplary results show that HTG is most beneficial under consideration of multiple techno-economic and environmental attributes. This result seems robust because HTG has the best values regarding life cycle emissions and production costs. Both criteria have a relatively high weighting which shows the importance of these values. Although HTG has the lowest current TRL compared to the other alternatives, the MCA procedure indicates that this technology is still promising. However, especially the weightings are of high importance. Thus, they have to be chosen very carefully. Figure 4 illustrates the important influence of criteria weightings exemplary for TRL assuming a proportional increase of all corresponding criteria weightings (sensitivity analysis).

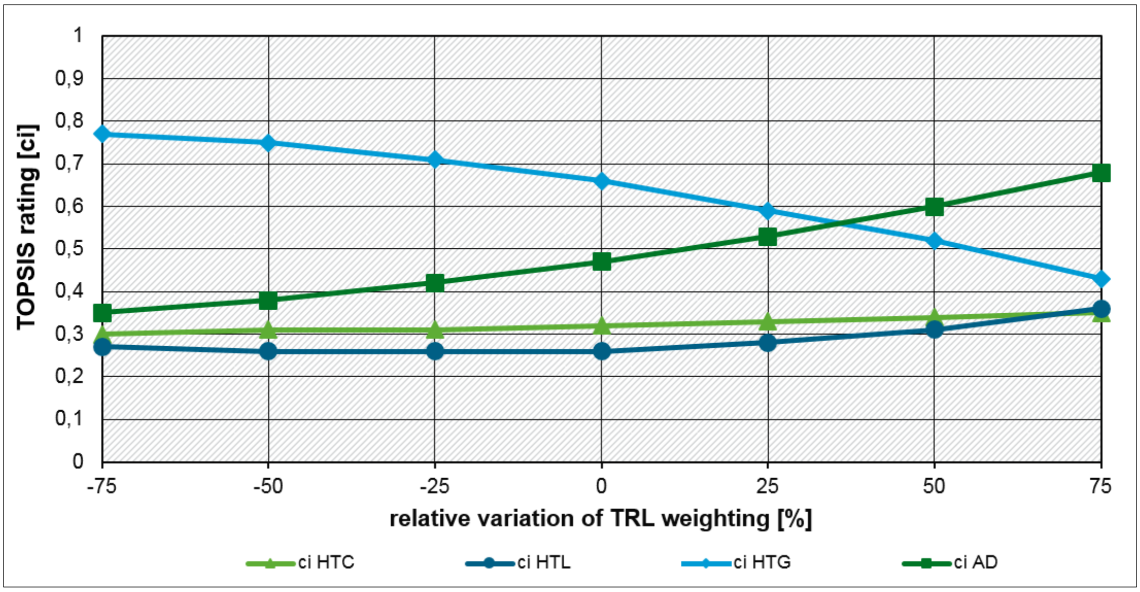

Figure 3. Sensitivity analysis for relative distance to ideal solution in relation to TRL

Comparison of study findings to comparable work

One particular issue about this field of work is that up to this date, no further multi-criteria approaches have been developed for assessing the suitability of hydrothermal processing wet bio-waste. Thus, this work provides novel information on how to deal with this issue by using an assessment framework that considers multiple attributes and specific requirements on HTP. However, as already mentioned in the introduction section several other studies assessed the hydrothermal treatment of wet bio-waste and residues using different assessment approaches mostly concentrating on just one dimension (e.g. life cycle assessment, economic assessment). Such studies are important for the proposed MCA approach, because generated data on economic or environmental assessment can be used as input for the calculations if they are comparable to each other. However, none of these studies assessed HTP in a multi-dimensional way.

Only few recent studies proposed assessment approaches for biomass conversion systems considering multiple attributes. Suwelack & Wüst (2015) developed a unified appraisal framework for biomass conversion systems that includes a MCA approach based on standardized data and impact levels. The approach was tested on random data for three biomass conversion systems considering seven criteria on social, environmental and economic issues. In general, this approach can be used to assess HTP if reliable data is available. However, the framework is not customized for HTP which is why the criteria are more general and specific methodological requirements for HTP evaluation are not considered. For example, very important criteria for HTP, e.g. process water pollution levels, are missing. The study of Billig & Thrän (2016) proposed a MCA approach to assess different bio-methane technology options. Also this approach seems transferable to some HTP concepts, especially HTG which also produces bio-methane. However, also in this approach relevant attributes and requirements for HTP assessment are missing which further confirms the necessity of the tailor-made MCA framework proposed by this study. Other recent studies suggesting multi-dimensional assessment frameworks for biomass conversion technologies (Martínez & Narváez 2016, Fazlollahi & Maréchal 2013, Gassner &

Maréchal 2009) also lack on missing criteria and less consideration of requirements for HTP evaluation.

Future perspectives and practical implications

Only a few industrial scale applications of HTP plants have been implemented in Europe, which is particularly due to techno-economic difficulties (cf. Reißmann 2018). Hence, the primary aim is to use this MCA tool for a comparative evaluation of different scenarios that assume full-scale application of HTP under certain requirements. Using the MCA approach, these scenarios can be compared regarding several relevant criteria. By varying criteria values for these scenarios, efficiency ranges can be identified which further indicate promising target corridors for future technology development and research priorities. For example, these indications can help policy to decide on which solutions for HTP process water treatment public funding may focus. In addition, decisions on regulatory adjustments, e.g. for the standardization of HTP products, can be partly based on promising development paths indicated by the MCA (e.g. energy carrier or material application markets). For private investors, indications on promising future technology paths and corresponding criteria value ranges will help to decide on investments for certain technological solutions considering specific requirements. In practice, the tool can be used for HTP site decisions (e.g. in relation to substrate availability), decisions on plant scale and promising markets. However, the tool will get more relevant for practice if more industrial scale plants are established. This is because the framework assumes that a functioning market exists and industrial scale plants operate under economic conditions.

Conclusion

This analysis proposed a MCA framework to assess the suitability of options for the hydrothermal treatment of wet bio-waste. To better validate the applicability of the method, exhaustive data computations have to be made. A major advantage of the procedure is that it needs relatively less input from the user. For example, developing the criteria “long list” and criteria weightings must usually executed just once and can be used for several analysis after. Thus, criteria derivation and weighting can be provided by experts before the user applies the approach for a case study or scenario analysis. TOPSIS is relatively easy to apply and the calculations can be made with Excel. However, the more criteria and alternatives are considered the complexity of calculations rises. Due to the relatively easy understandable approach, the results of the analysis are good to interpret and to communicate to the target audience. However, also some shortcomings are connected to the approach. A specific disadvantage of TOPSIS is that criteria must at least be ordinal measurable with similar distances on the measurement scale. This is sometimes not given and thus such criteria would not be applicable in TOPSIS. However, this problem can be solved by applying height preferences (e.g. through utility functions). Further, data is sometimes not available for relevant criteria. This is especially reasoned in the novelty of the technologies that is connected to an insufficient data situation. Hence, it seems useful to enlarge the approach with fuzzy logic or by means of a complementary self-learning algorithm. Additionally, it is important to carefully check the primary data sources for the used criteria on their comparability (e.g. checking if comparable assumptions were made to calculate this data).

Acknowledgements

We thank the anonymous reviewer for the suggestions and comments that helped in finalizing our manuscript.

References

Abdullah L (2013) Fuzzy Multi Criteria Decision Making and its Applications: A Brief Review of Category. *Procedia - Social and Behavioral Sciences* 97: 131-36. DOI: 10.1016/j.sbspro.2013.10.213.

Achillas C, Moussiopoulus N, Karagiannidis A, Banias G & Perkoulidis G (2013) The use of multi-criteria decision analysis to tackle waste management problems: a literature review. *Waste Management & Research* 31(2): 115-129. DOI: 10.1177/0734242X12470203.

Aggrey A, Dare P, Lei R & Gapes D (2012) Evaluation of a two-stage hydrothermal process for enhancing acetic acid production using municipal biosolids. *Water Sci Technol.* 65 (1):149-55. DOI: 10.2166/wst.2011.848.

Ahamed A, Yin K, Ng BJH, Ren F, Chang VWC, Wang JY (2016) Life cycle assessment of present and proposed food waste management technologies from environmental and economic impact perspectives. *J. Clean. Prod.* 131: 607-614. DOI: 10.1016/j.jclepro.2016.04.127.

Akadiri PO, Olomolaiye PO (2012) Development of sustainable assessment criteria for building materials selection. *Engineering, Construction and Architectural Management* 19: 666-687.

Akadiri PO, Olomolaiye PO, Chinyio EA (2013) Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Automation in Construction* 30: 113-125.

Akao, Y. (1992) *QFD-Quality Function Deployment*, Landsberg/Lech: Verlag Moderne Industrie. ISBN 3-478-91020-6.

Antonopoulos IS, Perkoulidis G, Logothetis D & Karkanias C (2014) Ranking municipal solid waste treatment alternatives considering sustainability criteria using the analytical hierarchical process tool. *Resources*, *Conservation and Recycling* 86: 149-59. DOI: 10.1016/j.resconrec.2014.03.002.

Arıkan E, Şimşit-Kalender ZT & Vayvay Ö (2017) Solid waste disposal methodology selection using multi-criteria decision making methods and an application in Turkey. *J. Clean. Prod.* 142(1): 403-12. DOI: 10.1016/j.jclepro.2015.10.054.

Asefi H & Lim S (2017) A novel multi-dimensional modeling approach to integrated municipal solid waste management. *J. Clean Prod.* 166: 1131-43. DOI: 10.1016/j.jclepro.2017.08.061.

Bennion EP, Ginosar DM, Moses J, Agblevor F & Quinn JC (2015) Lifecycle assessment of microalgae to bio-fuel: Comparison of thermochemical processing pathways. *Appl. Energ.* 154, 1062-1071. DOI: 10.1016/j.apenergy.2014.12.009.

Bezahdian M, Kazemzadeh RB, Albadvi A & Aghdasi A (2010) PROMETHEE: A comprehensive literature review on methodologies and applications. *European Journal of Operational Research* 200 (1): 198-2015. DOI: 10.1016/j.ejor.2009.01.021.

Bezama A (2016) Let us discuss how cascading can help implement the circular economy and the bio-economy strategies. *Waste Management & Research* 34(7): 593-594. DOI: 10.1177/0734242X16657973.

Billig, E. (2016) *Bewertung technischer und wirtschaftlicher Entwicklungspotenziale künftiger und bestehender Biomasse-zu-Methan-Konversionsprozesse (Evaluation of technological and economical development potentials of future and current biomass-to-methane conversion paths)*. PhD Dissertation, University of Leipzig.

Billig E & Thrän D (2016) Evaluation of biomethane technologies in Europe - Technical concepts under the scope of a Delphi-Survey embedded in a multicriteria analysis. *Energy* 114: 1176-86. DOI: 10.1016/j.energy.2016.08.084.

Billig E & Thrän D (2017) Renewable methane - A technology evaluation by multi-criteria decision making from a European perspective. *Energy* 139: 468-84. DOI: 10.1016/j.energy.2017.07.164.

BMEL – Federal Ministry of Food and Agriculture (2014) National Policy Strategy on Bioeconomy. Renewable resources and biotechnological processes as a basis for food, industry and energy. Division 531 – Strategy and Coordination of the

Directorate-General ‘Biobased business, sustainable agriculture and forestry’. Berlin: BMEL.

BMWi/Bundesministerium für Wirtschaft und Energie (2015) ZIM Erfolgsbeispiel: Innovative Verfahren und Produkte aus biogenen Reststoffen. Berlin: https://www.zim-bmwi.de/erfolgsbeispiele/innovative-verfahren-und-produkte-aus-biogenen-reststoffen/at_download/file (accessed January 19, 2018).

Brosowski A, Thrän D, Mantau U, Mahro B, Erdmann G, Adler P, Stinner W, Reinhold G, Hering T & Blanke C (2016) A review of biomass potential and current utilisation - Status Quo for 93 biogenic waste and residues in Germany. *Biomass and Bioenerg*. 95: 257-72. DOI: 10.1016/j.biombioe.2016.10.017.

Brans JP, Vincke P & Mareschal B (1986) How to select and how to rank projects: The Promethee method. *European Journal of Operational Research* 24(2): 228–238.

Brosowski, A. (2015) Rohstoffpotenziale für hydrothermale Prozesse (Raw material potentials for hydrothermal processes) In: Klemm, M., et al. (Eds.), *Innovationsforum Hydrothermale Prozesse*. Deutsches Biomasseforschungszentrum gGmbH, Leipzig: 21-24.

Chauhan A & Singh A (2016) A hybrid multi-criteria decision making method approach for selecting a sustainable location of healthcare waste disposal facility. *J. Clean. Prod.* 139: 1001-10. DOI: 10.1016/j.jclepro.2016.08.098.

Coelho LMG, Lange LC & Coelho HMG (2017) Multi-criteria decision making to support waste management: A critical review of current practices and methods. *Waste Management & Research* 35(1): 3-28. DOI: 10.1177/0734242X16664024.

DBFZ/Deutsches Biomasseforschungszentrum gGmbH (2016) *2. HTP-Fachforum: Biobasierte hydrothermale Prozesse – Technologien zur stofflichen und energetischen Nutzung (2nd HTP Experts forum: Biobased hydrothermal Processes – Technologies for a material and energetic use)*. Leipzig, Germany.

DFG/Deutsche Forschungsgemeinschaft (2013) *Safeguarding Good Scientific Practice – Memorandum*. Wiley VCH. Bonn. ISBN: 978-3-527-33703-3.

Elliott DC (2008) Catalytic hydrothermal gasification of biomass. *Biofuels, Bioprod. Bioref.* 2: 254-265. DOI: 10.1002/bbb.74.

European Commission (2012) Innovating for sustainable growth: A bioeconomy for Europe. Communication COM(2012) 60 final. Brussels.

EU/European Union (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives Text with EEA Relevance: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098 (accessed January 19, 2018).

Fazlollahi S & Maréchal F (2013) Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP). *Applied Thermal Engineering* 50(2): 1504-13. DOI: 10.1016/j.applthermaleng.2011.11.035.

Ferreira JA, Costa M, Tereso A & Oliveira JA (2015) A Multi-Criteria Decision Support System for a Routing Problem in Waste Collection. *International Conference on Evolutionary Multi-Criterion Optimization*: 388-402. DOI: 10.1007/978-3-319-15892-1_26.

Fiori L & Lucian M (2017) Hydrothermal Carbonization of Waste Biomass: Process Design, Modeling, Energy Efficiency and Cost Analysis. *Energies* 10(2): 211-239. DOI: 10.3390/en10020211.

Fontela E & Gabus A (1976) *The DEMATEL observer*, DEMATEL 1976 report. Battelle Geneva Research Center, Switzerland Geneva.

Ganzevles J & van Est R (2012) *PACITA Deliverable 2.2: TA Practices in Europa. Edited by PACITA* (Parliaments and Civil Society in Technology Assessment) consortium: Den Haag on behalf of the European Commission.

Gassner M & Maréchal F (2009) Methodology for the optimal thermo-economic, multi-objective design of thermochemical fuel production from biomass. *Computers & Chemical Engineering* 33(3): 769-81. DOI: 10.1016/j.compchemeng.2008.09.017.

Geldermann J & Lerche N (2014) *Leitfaden zur Anwendung von Methoden zur multikriteriellen Entscheidungsunterstützung (Guideline for the application of multi-criteria decision-making methods)*. University of Goettingen, Germany.

Greve T, Neudeck D, Rebling T & Röhrdanz M (2014). Prospects for the sustainable utilization of organic waste by Hydrothermal Carbonization. *Müll Abfall* 2: 86-93. Online in German: https://www.muellundabfall.de/MA.02.2014.086.

Hall, K., 2012. *Ganzheitliche Technologiebewertung – Ein Modell zur Bewertung unterschiedlicher Produktionstechnologien (Holistic Technology Assessment).* PhD Dissertation, Univerity of Leoben. Springer Fachmedien, Wiesbaden.

Hallesche Wasser und Stadtwirtschaft (2015) *Integrierte Verwertungsanlage und Strategie für kommunale Biomasse – HTC (Integrated treatment facility and strategy for municipal biomass – HTC)*. Halle/Saale, Germany.

Han R, Liu J, Zhao C, Li Y & Chen A (2016) Hydrogen-rich gas production via fast pyrolysis of biophysical dried sludge: Effect of particle size and moisture content on product yields and syngas composition. *Waste Management & Research* 34(6): 572-577.

Hariz HA, Dönmez CC & Sennaroglu B (2017) Siting of a central healthcare waste incinerator using GIS-based Multi-Criteria Decision Analysis. *J. Clean Prod.* 166: 1031-42. DOI: 10.1016/j.jclepro.2017.08.091.

Herva M & Roca E (2013) Ranking municipal solid waste treatment alternatives based on ecological footprint and multi-criteria analysis. *Ecological Indicators* 25: 77-84. DOI: 10.1016/j.ecolind.2012.09.005.

Hwang CL & Yoon K (1981) *Multiple Attribute Decision Making – Methods and Applications. A State-of-the-Art Survey*. Berlin – Heidelberg – New York.

Jovanovic S, Savic S, Jovicic N, Boskovic G & Djordjevic Z (2016) Using multi-criteria decision making for selection of the optimal strategy for municipal solid waste management. *Waste Management & Research* 34(9): 884-895. DOI: 10.1177/0734242X16654753.

Khanmohammadi Z, Afyuni M & Mosaddeghi MR (2015) Effect of pyrolysis temperature on chemical and physical properties of sewage sludge biochar. *Waste Management & Research* 33(3): 275-283.

KIC InnoEnergy (2015) *Energy from Chemical Fuels Strategy Roadmap 2015-2019, v 2.0.* Eindhoven, Netherlands.

Klavenieks K, Dzene KP & Blumberga D (2017) Optimal strategies for municipal solid waste treatment – environmental and socio-economic criteria assessment. *Energy Procedia* 128: 512-19. DOI: 10.1016/j.egypro.2017.09.071.

Klemm M, Kaltschmitt M, Thrän D & Viehmann C. (2009) *Hydrothermale Carbonisierung im Vergleich zu anderen Verfahren zu energetischen Nutzung nasser Biomasse*. Presentation, Leipzig, Germany.

Klingler D & Vogler H (2010) Influence of process parameters on the hydrothermal decomposition and oxidation of glucose in sub- and supercritical water. *J. Supercrit. Fluids* 55 (1): 259-270. DOI: 10.1016/j.supflu.2010.06.004.

Kong L, Li G, Zhang B, He W & Wang H (2008) Hydrogen Production from Biomass Wastes by Hydrothermal Gasification. *Energ. Sourc.* 30(13): 1166-78. DOI: 10.1080/15567030701258246.

Kruse A (2009) Hydrothermal biomass gasification. *The Journal of Supercritical Fluids* 47(3): 391-99. DOI: 10.1016/j.supflu.2008.10.009.

Kruse A, Funke A & Titrici MM (2013) Hydrothermal conversion of biomass to fuels and energetic materials. *Curr. Opin. in Chem. Biol*. 17: 515-521. DOI: 10.1016/j.cbpa.2013.05.004.

Libra JA, Ro KS, Kammann C, Funke A, Berge N, Neubauer Y, Titrici MM, Fühner C, Bens O, Kern J & Emmerich KH (2011) Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. *Biofuels* 2 (1): 89-124. DOI: 10.4155/bfs.10.81.

Lin Y, Ma X, Peng X & Yu Z (2017) Forecasting the byproducts generated by hydrothermal carbonisation of municipal solid wastes. *Waste Management & Research* 35(1): 92–100.

Liu HC, Wu J & Li P (2013) Assessment of health-care waste disposal methods using a VIKOR-based fuzzy multi-criteria decision making method. *Waste Management* 33(12): 2744-51. DOI: 10.1016/j.wasman.2013.08.006.

Liu HC, You JX, Fan XJ & Chen YZ (2014) Site selection in waste management by the VIKOR method using linguistic assessment. *Applied Soft Computing* 21: 453-61. DOI: 10.1016/j.asoc.2014.04.004.

Lu X, Jordan B, Berge ND (2012) Thermal conversion of municipal solid waste via hydrothermal carbonization: Comparison of carbonization products to products from current waste management techniques. *Waste Management* 32(7): 1353-65. DOI: 10.1016/j.wasman.2012.02.012.

Majumdar A, Hazra T & Dutta A (2017) Landfill Site Selection by AHP Based Multi-criteria Decision Making Tool: A Case Study in Kolkata, India. *Journal of The Institution of Engineers (India): Series A* 98(3): 277-283. DOI: 10.1007/s40030-017-0211-5.

Martínez J & Narváez RA (2016) Use of Multicriteria Decision Making (MCDM) Methods for Biomass Selection Aimed to Fischer Tropsch Processes. International Journal of Engineering Trends and Technology 34(6): 266-72. DOI: 10.14445/22315381/IJETT-V34P254.

Makan A, Malamis D, Assobhei O & Loizidou M (2013) Multi-criteria decision aid approach for the selection of the best compromise management scheme for the treatment of municipal solid waste in Morocco. *International Journal of Environment and Waste Management* 12(3). DOI: 10.1504/IJEWM.2013.056197.

Mardani A, Jusoh A, Nor KMD, Khalifah Z, Zakwan N &Valipour A (2015) Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014. *Economic Research* 28(1): 516-571. DOI: 10.1080/1331677X.2015.1075139.

Milutinović B, Stefanović G, Dassistic M, Marković D & Vučković G (2014) Multi-criteria analysis as a tool for sustainability assessment of a waste management model. *Energy* 74: 190-201. DOI: 10.1016/j.energy.2014.05.056.

Milutinović B, Stefanović G, Đekić PS, Mijailović I & Tomić M (2017) Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multi-criteria analysis. *Energy* 137: 917-26. DOI: j.energy.2017.02.167.

Mir MA, Ghazvinei PT, Sulaiman NMN, Basri NEA, Saheri S, Mahmood NZ, Jahan A, Begum RA & Aghamohammadi N (2016) Application of TOPSIS and VIKOR improved versions in a multi criteria decision analysis to develop an optimized municipal solid waste management model. *J. .Environ. Management* 166: 109-15. DOI: 10.1016/j.jenvman.2015.09.028.

Nielfa A, Cano R, Pérez A & Fdez-Polanco M (2015) Co-digestion of municipal sewage sludge and solid waste: Modelling of carbohydrate, lipid and protein content influence. *Waste Management & Research* 33(3): 241-249.

Nouri J, Omrani GA, Arjmandi A & Kermani M (2014) Comparison of solid waste management scenarios based on life cycle analysis and multi-criteria decision making (Case study: Isfahan city). *Iranian Journal of Science & Technology* 38(A3): 257-264.

Nouri D, Sabour MR & GhanbarzadehLak M (2018) Industrial solid waste management through the application of multi-criteria decision-making analysis: a case study of Shamsabad industrial complexes. *Journal of Material Cycles and Waste Management* 20(1): 43-58. DOI: 10.1007/s10163-016-0544-6.

Oliveira I, Blöhse D, Ramke HG (2013) Hydrothermal carbonization of agricultural residues. *Bioresource Technol.* 142: 138-46. DOI: 10.1016/j.biortech.2013.04.125.

Opricovic SC & Miloradov M (2016) Multi-criteria selection of municipal waste treatment system using VIKOR method. *International Journal of Environment and Waste Management* 18(1). DOI: 10.1504/IJEWM.2016.080261.

Opricovic S. (1998) Multicriteria optimization of civil engineering systems. *Fac. Civ. Eng. Belgrade* 2: 5–21.

Panagiotidou N, Stavrakakis GS & Diakaki C (2015) Sustainable urban solid waste management planning with the use of an advanced interactive decision support system based on the PROMETHEE II method. *International Journal of Decision Support Systems* 1(3). DOI: 10.1504/IJDSS.2015.070173.

Parawina W, Read JS, Mattiasson B & Björnsson L (2008) Energy production from agricultural residues: High methane yields in pilot-scale two-stage anaerobic digestion. *Biomass and Bioenergy* 32(1): 44-50. DOI: 10.1016/j.biombioe.2007.06.003.

Pehlken A, Madena K, Aden C & Klenke T (2016) Forming stakeholder alliances to unlock alternative and unused biomass potentials in bioenergy regions. *J. Clean. Prod.* 110: 66-77. DOI: 10.1016/j.jclepro.2015.05.052.

Peters ML & Zelewski S (2007) TOPSIS als Technik zur Effizienzanalyse (TOPSIS as technique for efficiency analysis). *WiSt Heft* 36 (1): 9-15.

Peters ML & Zelewski S (2004) Möglichkeiten und Grenzen des „Analytical Hierarchy Process“ (AHP) als Verfahren zur Wirtschaftlichkeitsanalyse (Possibilities and limites of AHP as approach for efficiency analysis). *Zeitschrift für Planung und Unternehmenssteuerung* 15: 295-324.

Poulsen TG, Astrup T, Ragossnig AM (2012) Biomass waste – the way ahead. *Waste Management & Research* 30(10): 999-1000. DOI: 10.1177/0734242X12461577.

Prabhu MS, Mutnuri S (2016) Anaerobic co-digestion of sewage sludge and food waste. *Waste Management & Research* 34(4): 307-315.

Reißmann D, Thrän D & Bezama A (2018) Hydrothermal Processes as treatment paths for biogenic residues in Germany: A review of the technology, sustainability and legal aspects. *J. Clean. Prod*. 172: 239-52. DOI: 10.1016/j.jclepro.2017.10.151.

Rohweder JP, Kasten G, Malzahn D, Piro A & Schmid J (2015) Informationsqualität - Definitionen, Dimensionen und Begriffe (Information quality – definitions, dimensions and terms), in: Hildebrand, K. et al., (Ed.): *Daten- und Informationsqualität*. Springer Fachmedien, Wiesbaden. DOI: 10.1007/978-3-658-09214-6_2.

Rowe G, Wright G (1999) The Delphi technique as a forecasting tool: issues and analysis. *International Journal of Forecasting* 15: 353-75.

Rulkens W (2008) Sewage Sludge as a Biomass Resource for the Production of Energy: Overview and Assessment of the Various Options. *Energy & Fuels* 22(1): 9-15. DOI: 10.1021/ef700267m.

Saaty TL (1990) How to make a decision: The analytic hierarchy process. *European Journal of Operational Research* 48 (1): 9-26. DOI: 10.1016/0377-2217(90)90057-I.

Saaty TL (1987) The analytic hierarchy process - what it is and how it is used. *Mathematical Modelling* 9 (3-5): 161–176.

Santos MK, Danilevicz AMF & Tubino RMC (2017) Environmental service providers assessment: A multi-criteria model applied to industrial waste. *J. Clean. Prod.* 159: 374-87. DOI: 10.1016/j.jclepro.2017.05.035.

Saxena RC, Adhikari DK & Goyal HB (2009) Biomass-based energy fuel through biochemical routes: A review. *Renewable and Sustainable Energy Reviews* 13(1): 167-178. DOI: 10.1016/j.rser.2007.07.011.

Scheffzcik, W (2003) Technikbewertung und Technikfolgenabschätzung - ein Beitrag zur Entwicklung des Technikunterrichts an allgemeinbildenden Schulen (Technology Assessment – a contribution for the development of technology lessons at general eduction schools). PhD Thesis, Oldenburg.

Searle S & Malins C (2015) National case studies on potential waste and residue availability for cellulosic biofuel production in the EU. The International Council on Clean Transportation. Online: http://www.theicct.org/sites/default/files/ICCT_EU-national-wastes-residues_Feb2015.pdf, (accessed: August 4, 2017)

Shahba S, Arjmandi R, Monavari M & Ghodusi J (2017) Application of multi-attribute decision-making methods in SWOT analysis of mine waste management (case study: Sirjan's Golgohar iron mine, Iran). *Resources Policy* 51: 67-76. DOI: 10.1016/j.resourpol.2016.11.002.

Soltani A, Hewage K, Reza B & Sadiq R (2015) Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management: A review. *Waste Management* 35: 318-28. DOI: 10.1016/j.wasman.2014.09.010.

Stafford W, Lotter A, Brent A & Maltizt G (2017) *Biofuels Technology – A look forward*. WIDER Working Paper 2017/87. ISBN 978-92-9256-311-0.

Suwelack K & Wüst D (2015) An approach to unify the appraisal framework for biomass conversion systems. *Biomass and Bioenergy* 83: 354-65. DOI: 10.1016/j.biombioe.2015.10.012.

Thampi A & Rao B (2015) Application of Multi-criteria Decision Making Tools for Technology Choice in Treatment and Disposal of Municipal Solid Waste for Local Self Government Bodies - A Case Study of Kerala, India. *Journal of Solid Waste Technology and Management* 41(1): 84-95. DOI: 0.5276/JSWTM.2015.84.

Thrän D & Bezama A (2017) The knowledge-based bioeconomy and its impact in our working field. Waste Management & Research 35(7): 689-90. DOI: 10.1177/0734242X17719605.

Triantaphyllou, E (2000) *Multi-criteria Decision Making Methods: A Comparative Study*. Springer-Verlag, Boston, USA. DOI: 10.1007/978-1-4757-3157-6.

Tröger N, Kröger M, Richter D, Förster S, Schröder J, Zech K, Liemen F, Stahl R & Müller-Langner F (2013) Utilization of biogenic residues and wastes in thermochemical systems for the production of fuels: current status of the project. *Biofuels, Bioprod. Bioref.* 7(1): 12-23. DOI: 10.1002/bbb.1371.

U.S. Department of Energy (2014) Biomass Direct Liquefaction Options: TechnoEconomic and Life Cycle Assessment. Washington, USA. Online: www.pnnl.gov/main/publications/external/.../PNNL-23579.pdf.

U.S. Department of Energy (2016) Hydrothermal Liquefaction and Upgrading of Municipal Wastewater Treatment Plant Sludge: A Preliminary Techno-Economic Analysis. Richland, USA: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25464.pdf.

Valenzuela-Venegas G, Salgado JC & Diaz-Alvarado FA, (2016) Sustainability indicators for the assessment of eco-industrial parks: classification and criteria for selection. *J. Clean. Prod.* 133: 99-116. DOI: 10.1016/j.jclepro.2016.05.113.

Vučijak B, Kurtagić SM & Silajdžic I (2016) Multicriteria decision making in selecting best solid waste management scenario: a municipal case study from Bosnia and Herzegovina. *Journal of Cleaner Production* 130: 166-74. DOI: 10.1016/j.jclepro.2015.11.030.

Wang Z, Ren J, Goodsite ME & Xu G (2018) Waste-to-energy, municipal solid waste treatment, and best available technology: Comprehensive evaluation by an interval-valued fuzzy multi-criteria decision making method. *J. Clean. Prod.* 172: 887-899. DOI: 10.1016/j.jclepro.2017.10.184.

Wzorek M & Tańczuk M (2015) Production of biosolid fuels from municipal sewage sludge: Technical and, economic optimisation. *Waste Management & Research* 33(8): 704-714.

Xiao LP, Shi ZJ, Xu F & Sun RC (2012) Hydrothermal carbonization of lignocellulosic biomass. *Bioresour. Technol.* 118: 619-23. DOI: 10.1016/j.biortech.2012.05.060.

Yap HY & Nixon JD (2015) A multi-criteria analysis of options for energy recovery from municipal solid waste in India and the UK. *Waste Management* 46: 265-77. DOI: 10.1016/j.wasman.2015.08.002.

Zare R, Nouri J, Abdoli MA, Atabi F & Alavi M (2016) The Integrated Fuzzy AHP and Goal Programing Model Based on LCA Results for Industrial Waste Management by Using the Nearest Weighted Approximation of FN: Aluminum Industry in Arak, Iran. *Advances in Materials Science and Engineering*. DOI: 10.1155/2016/1359691.

Zhang L, Xu C, Champagne P & Mabee W (2014) Overview of current biological and thermo-chemical treatment technologies for sustainable sludge management. *Waste Management & Research* 32(7): 586-600

Zhang, Y (2010) Hydrothermal Liquefaction to Convert Biomass into Crude Oil, in: Hans P. Blaschek H.P., Ezeji, T.C., Scheffran J. (Ed.) *Biofuels from Agricultural Wastes and Byproducts*. Wiley-Blackwell, Hoboken, U.S.

Supplementary Information (SI)

Appendix A – Check of MCA methods on requirement fulfilment

Analytical Hierarchy Process (AHP):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of AHP that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of AHP that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – if data availability is given, all quantitative criteria can be considered.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – qualitative criteria can be used but must at least be measurable on an ordinal scale.
Applicability	*Yes* – the AHP is a relative complex method because mathematical knowledge is necessary to solve matrix calculations. However, several software programs can assist to solve the calculations. Because the AHP is often applied in science and practice the applicability must be given.
Objectivity	Involvement of expert feedback in criteria selection: *No* – the criteria selection is applied by the decision-maker, expert involvement is not an integral part. Also, current applications do not involve experts into the criteria selection.
	Involvement of expert feedback in criteria weighting: *No/Yes* – as suggested by Saaty, the original version of AHP does not need expert involvement for criteria weighting because this is made by the decision-maker. Current applications try to the involve experts through surveys (e.g. Delphi surveys).
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of the classic AHP. However, subsequent sensitivity analysis are sometimes applied to interpret the results of AHP. Through this form of analysis also benchmarks can be generated.

Decision-Making Trial and Evaluation Laboratory (DEMATEL):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of DEMATEL that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of DEMATEL that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* –quantitative criteria can be considered.
	Consideration of qualitative techno-economic and environmental criteria: *Yes* – because DEMATEL primary measures the interdependencies between criteria through expert estimations, it is not necessary that all criteria are quantitative. Hence also qualitative criteria can be considered.
Applicability	*No/Yes* – the procedure itself is relatively simple and needs no in-depth mathematical knowledge to be applied. However, because expert involvement is needed to estimate the interdependencies of criteria the effort is relatively high.
Objectivity	Involvement of expert feedback in criteria selection: *No* – criteria selection is not a part of DEMATEL. Given criteria are checked regarding their independencies.
	Involvement of expert feedback in criteria weighting: *No* – also criteria weighting is no part of DEMATEL.
Adaptability	*No/Yes* – after expert estimations have been made it is very difficult to adapt the procedure (e.g. through introducing of new criteria). However, further estimations can be made if necessary, but this increases the effort considerable.
Benchmarking	*No* – benchmarking is no part of DEMATEL.

Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of PROMETHEE that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of PROMETHEE that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – if data is available, all quantitative criteria can be considered.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – because PROMETHEE uses preference functions for all criteria also qualitative criteria can be considered. However, they must be at least ordinal.
Applicability	*Yes* – several software applications can assist to solve the calculations.
Objectivity	Involvement of expert feedback in criteria selection: *No* – criteria selection is not a part of PROMETHEE. Criteria must be already given.
	Involvement of expert feedback in criteria weighting: *No/Yes* – a weighting procedure is not defined by PROMETHEE and can be selected by the user. Hence, experts can be involved or not.
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of the PROMETHEE. However, subsequent sensitivity analysis are sometimes applied to interpret the results. Hence, also benchmarks can be generated.

Quality Function Deployment (QFD):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *No/Yes* – there are no assumptions of QFD that forbid this. However, the house of quality (as comparison matrix between attributes of alternatives) is only useful for very similar alternatives because customer requirements are maybe not comparable.
	Consideration of energetic and material treatment paths: *No/Yes* – there are no assumptions of QFD that forbid this. However, the house of quality (as comparison matrix between alternatives) is only useful for very similar alternatives because customer requirements are maybe not comparable.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – due to that QFD simply sorts the criteria within a matrix and seeks for correlation (house of quality) all kind of criteria can be considered in general.
	Consideration of qualitative techno-economic and environmental criteria: *Yes* – due to that QFD simply sorts the criteria within a matrix and seeks for correlation (house of quality) all kind of criteria can be considered in general.
Applicability	*No/Yes* – QFD is a relative simple analytical method which can be used without complex mathematics. Generally no software applications are necessary. However, because the analysis is primary based on customer product expectations, a high effort for market research is necessary. Next to this, creating the house of quality is hard without detailed background knowledge on the procedure of QFD.
Objectivity	Involvement of expert feedback in criteria selection: *No/Yes* – usually the internal project members define the product functions as one side of criteria and the customer define their requirements as another part of criteria. An objective expert feedback on this selection is normally no part of QFD.
	Involvement of expert feedback in criteria weighting: *No/Yes* – prioritization of criteria is usually done by the team members and also not verified through expert feedback. However, also the team members are experts in their fields.
Adaptability	*No/Yes* – QFD is no flexible procedure, because it only depends on creating the house of quality. However, further customer estimations or product functions can be added which makes the procedure in part adaptable. Including further alternatives that are not competitive to the primary alternatives is difficult because product functions as well as customer expectations may not match which makes them not comparable.
Benchmarking	*No* – a benchmarking of weightings or criteria at it is intended for the HTP method is no part of QFD. Also subsequent sensitivity analysis are usually not applied after QFD.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of TOPSIS that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of TOPSIS that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – if criteria are measurable on a cardinal scale all kind of quantitative criteria can be used.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – criteria must be cardinally measurable which is often not given for qualitative criteria. However, this can be met by using height preferences for creating at least ordinal scales with similar distances.
Applicability	*Yes* – TOPSIS is a very intuitive and relative simple procedure. No complex mathematics are necessary. Software applications are available for extensive calculations.
Objectivity	Involvement of expert feedback in criteria selection: *No* – expert feedback for criteria selection is no necessary part of TOPSIS.
	Involvement of expert feedback in criteria weighting: *No/Yes* – a weighting procedure is not defined by TOPSIS and can be selected by the user. Hence, experts can be involved or not.
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of TOPSIS. However, subsequent sensitivity analysis are sometimes applied to interpret results. Hence, also benchmarks can be generated.

Vise Kriterijumska Optimizacija I Kompromisno. Resenje (VIKOR):

Holistic nature	Consideration of thermo-chemical and bio-chemical conversion paths: *Yes* – there are no assumptions of VIKOR that forbid this.
	Consideration of energetic and material treatment paths: *Yes* – there are no assumptions of VIKOR that forbid this.
Multi dimensionality	Consideration of quantitative techno-economic and environmental criteria: *Yes* – all kind of quantitative criteria can be considered by VIKOR.
	Consideration of qualitative techno-economic and environmental criteria: *No/Yes* – qualitative criteria can be considered if they are at least measurable on an ordinal scale.
Applicability	*No/Yes* – VIKOR is more complex and therefore harder to understand than other comparable MCA methods which reduce the intuitive interpretation of results. However, several software applications can assist to solve the calculations which reduces the effort at least in part.
Objectivity	Involvement of expert feedback in criteria selection: *No* – expert feedback for criteria selection is no necessary part of VIKOR.
	Involvement of expert feedback in criteria weighting: *No/Yes* – a weighting procedure is not defined by VIKOR and can be selected by the user. Hence, experts can be involved or not. Usually, weights are defined due to preferences of the decision-maker.
Adaptability	*Yes* – the procedure is linear, but adaptions of previous steps can be made if necessary.
Benchmarking	*No/Yes* – benchmarking is not part of VIKOR. However, subsequent sensitivity analysis can be applied to interpret results and generate benchmarks.

Appendix B – Exemplary filled sample technology “fact sheet”

<table>
<tr><td>Evaluation purpose</td><td colspan="2">Assess the suitability of fictive HTP concepts on the use of wet biogenic residues.</td></tr>
<tr><td>Geographic framework</td><td colspan="2">Germany.</td></tr>
<tr><td>Time period</td><td colspan="2">No specific time period, because several data sets with different time frames were used for the fictive concepts.</td></tr>
<tr><td rowspan="26">Description of considered technology concepts</td><td colspan="2">Hydrothermal Carbonization concept</td></tr>
<tr><td>Parameter</td><td>Specification</td></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues, sewage sludge, animal excreta</td></tr>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>10-30 bars</td></tr>
<tr><td>Reactor temperature range</td><td>160-250 °C</td></tr>
<tr><td>Reaction time range</td><td>1-72 h</td></tr>
<tr><td>End-product</td><td>Hydro-coal</td></tr>
<tr><td colspan="2">Hydrothermal Liquefaction concept</td></tr>
<tr><td>Parameter</td><td>Specification</td></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues, sewage sludge, animal excreta, algae</td></tr>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>40-200 bars</td></tr>
<tr><td>Reactor temperature range</td><td>180-400 °C</td></tr>
<tr><td>Reaction time range</td><td>10-240 min.</td></tr>
<tr><td>End-product</td><td>HTL-oil</td></tr>
<tr><td colspan="2">Hydrothermal Gasification concept</td></tr>
<tr><td>Parameter</td><td>Specification</td></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues, sewage sludge, animal excreta</td></tr>
</table>

<table>
<tr><td></td><td>
<table>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>230-400 bars</td></tr>
<tr><td>Reactor temperature range</td><td>350-400 °C</td></tr>
<tr><td>Reaction time range</td><td>5-10 min.</td></tr>
<tr><td>End-product</td><td>HTG-gas</td></tr>
</table>
</td></tr>
<tr><td>Reference system(s)</td><td>Anaerobic Digestion (AD) as competitive system on substrate markets:
<table>
<tr><th>Parameter</th><th>Specification</th></tr>
<tr><td>Substrate(s)</td><td>Lignocellulose residues,
animal excreta</td></tr>
<tr><td>Reactor type</td><td>Continuous flow system</td></tr>
<tr><td>Reactor pressure range</td><td>Ambient pressure</td></tr>
<tr><td>Reactor temperature range</td><td>32-65 °C</td></tr>
<tr><td>Reaction time range</td><td>35-80 days</td></tr>
<tr><td>End-product</td><td>Biogas</td></tr>
</table>
</td></tr>
<tr><td>System boundaries</td><td>(1) Feedstock provision & substrate pre-treatment → (2) Conversion & Refinement → (3) Products & By-products → (4) Product Usage</td></tr>
<tr><td>Check on data availability</td><td>Data from scientific studies and technical reports. Data refers to specific case studies (e.g. modelled plants, demonstration and pilot plants, and laboratory tests) and average values.</td></tr>
</table>

Appendix C – Criteria "long list"

Criteria	Definition	Unit	Relevant process step
K.O. criterion (Fulfillment must be given for every assessment alternative)			
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
Input metrics/costs (to be minimized)			
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
Distance to suitable substrates	Transport distance of suitable substrates from place of occurrence to treatment plant.	Kilometer (km)	Feedstock provision
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
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
Output metrics/benefits (to be maximized)			
TRL	Classification of the level of development of a considered technology according to ISO 16290 (ISO 2013).	Assessed on a scale from 1 to 9	All process steps

Material efficiency	Relation of product output to raw material input (Eichhorn 2000).	Percent of functional unit	Conversion/ refinement
Energy efficiency	Relation of energy output to energy input (Eichhorn 2000).	Percent of functional unit	Conversion/ refinement
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
Carbon share of end-product	Share of carbon in HTC coal in relation to total mass volume.	Percent	Product Usage
Share of recycled phosphorus	Share of phosphorus that is recycled in relation to the total substrate feed-in.	Percent	Recycling

Appendix D – Applied data for preliminary calculations

Definitions of data types

- *Specific data* means that these values refer to exemplary processes and plants
- *Average data* means that these values are the average of data from several (at least two) processes and plants
- *Generic data* means that these values are the result of comprehensive meta studies and mostly typical for the whole process type

Criteria	Unit	Data type	Value(s)	References
Data on HTC				
Production costs	EURct/kWh	average	6.5	Reißmann et al. 2018
Life cycle emissions	gCO2eq./$MJ_{product}$	specific	45	Reißmann et al. 2018
TRL	-	generic	6.5	KIC InnoEnergy 2015
Material efficiency	% kg	specific	16.5	GRENOL 2014
Energy efficiency	% MJ	average	80	Klemm et al. 2009
Calorific value of end-product	MJ/kg dry matter	average	24.5	Reißmann et al. 2018
Data on HTL				
Production costs	EURct/kWh	specific	11.8	Reißmann et al. 2018
Life cycle emissions	gCO2eq./$MJ_{product}$	specific	-5	Reißmann et al. 2018
TRL	-	generic	7	Stafford et al. 2017
Material efficiency	% kg	specific	80	Toor et al. 2010
Energy efficiency	% MJ	average	78	Klemm et al. 2009
Calorific value of end-product	MJ/kg dry matter	average	35	Reißmann et al. 2018
Data on HTG				
Production costs	EURct/kWh	specific	3	Reißmann et al. 2018
Life cycle emissions	gCO2eq./$MJ_{product}$	specific	-600	Reißmann et al. 2018
TRL	-	generic	5	Vogel 2016
Material efficiency	% kg	specific	26	Kumabe et al. 2017
Energy efficiency	% MJ	average	76.5	Klemm et al. 2009
Calorific value of end-product	MJ/kg dry matter	specific*	21.65	Elsayed et al. 2015
Data on AD				
Production costs	EURct/kWh	average	7.5	Bundesnetzagentur 2014
Life cycle emissions	gCO2eq./$MJ_{product}$	average	-140	Fehrenbach et al. 2009
TRL	-	generic	9	Bundesregierung 2014

Material efficiency	% kg	specific	13	Volkmann 2009
Energy efficiency	% MJ	average	48	Reißmann et al. 2018
Calorific value of end-product	MJ/kg dry matter	average	31.25	FNR 2014

*) calculated with conversion factor of conventional natural gas.

Additional references for Supplementary Information

Brandt, F (2004) Brennstoffe und Verbrennungsrechnung (Calculation of fuels and combustion). Vulkan Verlag Essen, 3rd Edition, ISBN 3-8027-5801-3.

Bronner, A (2013) Angebots- und Projektkalkulationen: Leitfaden für technische Betriebe (Calculation of offers and projects: Guidelines for technical firms), pp. 9-10, Berlin/Heidelberg, Germany: Springer-Verlag.

Bundesnetzagentur (2014) Bericht der Bundesnetzagentur über die Auswirkungen der Sonderregelungen für die Einspeisung von Biogas in das Erdgasnetz. Bonn, Germany: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/Biogas/Biogas_Monitoring/Biogas_Monitoringbericht_2014.pdf?__blob=publicationFile&v=1 (accessed January 19, 2018).

Bundesregierung (2014) Roadmap Bioraffinerien im Rahmen der Aktionspläne der Bundesregierung zur stofflichen und energetischen Nutzung nachwachsender Rohstoffe. Berlin, Germany: https://www.bmel.de/SharedDocs/Downloads/Broschueren/RoadmapBioraffinerien.pdf?__blob=publicationFile (accessed January 19, 2018)

Eichhorn, P (2000) *Das Prinzip der Wirtschaftlichkeit*, p. 15., Wiesbaden, Germany: Gabler Verlag. DOI: 10.1007/978-3-322-93146-7.

Elsayed S, Boukis N, Sauer J, Patzelt D, Kerner M & Hindersin S (2015) Algal Cultivation and Hydrothermal Gasification. *Energiewirtschaftliche Tagesfragen* 65(1): 104-106.

Fettig J, Austermann-Haun U, Liebe H, Meier JF & Wichern M (2015) Ein Konzept zur Behandlung von Prozesswässern aus der hydrothermalen Carbonisierung. KA Korrespondenz Abwasser und Abfall 62(6): 529-536.

FNR – Fachagentur für Nachwachsende Rohstoffe (2014) Biogas: Faustzahlen: https://biogas.fnr.de/daten-und-fakten/faustzahlen/ (accessed January 19, 2018).

Fehrenbach H, Reinhardt G, Vogt R, Köppen S (2009) Einsatz von Biomethan aus Sicht des Klimaschutzes. Presentation, Berlin, Germany:

GRENOL (2016) Hydro-/Vapothermal Carbonization: Schlüsseltechnologie in der weltweiten Abfallbehandlung. Presentation: http://intercentre.de/wp-content/uploads/2016/10/HTCVTC_de.pdf (accessed January 19, 2018).

ISO (2006) ISO 14040:2006 *Environmental management -- Life cycle assessment -- Principles and framework*: https://www.iso.org/standard/37456.html (accessed January 19, 2018)

ISO (2013) ISO 16290:2013 Space systems - Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment: https://www.iso.org/standard/56064.html (accessed January 19, 2018).

Kumabe K, Itoh N, Matsumoto K & Hasegawa T (2017) Hydrothermal gasification of glucose and starch in a batch and continuous reactor. *Energy Reports* 3: 70-75. DOI: 10.1016/j.egyr.2017.04.001.

Toor SS, Rosendahl L & Rudolf A (2011) Hydrothermal liquefaction of biomass: A review of subcritical water technologies. *Energy* 36(5): 2328-2342. DOI: 10.1016/j.energy.2011.03.013.

Vogel, F (2016) Pilot-scale demonstration of the hydrothermal gasification of wet biomass. Presentation, Switzerland: http://www.sccer-biosweet.ch/wp-content/uploads/Vogel-Biomass-for-Swiss-Energy-Future-2016.pdf (accessed January 19, 2018).

Volkmann, D (2009) Biogas – anaerobe Vergärung von Klärschlamm und kommunalen Abfällen. Presentation, Minsk, Belarus.