Supplementary Information (SI) to article “How to identify suitable ways for the hydrothermal treatment of wet bio-waste? A critical review and methods proposal”

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>Assess the suitability of fictive HTP concepts on the use of wet biogenic residues.</td></tr>
<tr><td>Geographic framework</td><td>Germany.</td></tr>
<tr><td>Time period</td><td>No specific time period, because several data sets with different time frames were used for the fictive concepts.</td></tr>
<tr><td rowspan="3">Description of considered technology concepts</td><td>Hydrothermal Carbonization concept
<table>
<tr><th>Parameter</th><th>Specification</th></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>
</table></td></tr>
<tr><td>Hydrothermal Liquefaction concept
<table>
<tr><th>Parameter</th><th>Specification</th></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>
</table></td></tr>
<tr><td>Hydrothermal Gasification concept
<table>
<tr><th>Parameter</th><th>Specification</th></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>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>
</table>

System boundaries	(1) Feedstock provision & substrate pre-treatment → (2) Conversion & Refinement → (3) Products & By-products → (4) Product Usage
Check on data availability	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.

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.

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