Reißmann, D., **Thrän, D.**, **Bezama, A.** (2020):
What could be the future of hydrothermal processing wet biomass in Germany by 2030? A semi-quantitative system analysis
Biomass Bioenerg. **138** , art. 105588

What could be the future of hydrothermal processing wet biomass in Germany by 2030? A semi-quantitative system analysis

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

The hydrothermal conversion of wet biomass into carbon-rich products is credited with a high potential. But in Germany corresponding large scale facilities have not been established yet. In order to investigate why this is the case, we have identified key factors for the development of hydrothermal processes (HTP) in Germany in previous works. Based on this, this study presents three scenarios of HTP development in Germany by 2030 that represent different combinations of key development factors considering high probability and relevance of occurrence as well as risks in case of factors non-occurrence. Using fuzzy cognitive mapping, connections between the factors are modelled. Further, the system is analysed on its reaction to the scenarios, so that important impacts can be identified. A punctual result is, that for the scenario including most relevant key factors, a normative and economic stabilization of the system is observable. This is above all reasoned in the assumed supporting legal framework. Thus, this path is the most suitable for a successful HTP development in Germany according to this analysis.

Keywords: Hydrothermal Processes; Biogenic residues; Germany; Scenario analysis; Fuzzy cognitive map

Words (without matrices, appendix and literature): 5991

1. Introduction

For the future establishment of a resource-efficient circular- and bio-economy, the most efficient use of biogenic residues is of great interest [1, 2, 3, 4, 5, 6]. Hydrothermal processes (HTP) are currently credited with a high potential to lead to a more efficient use of wet biomass. HTP are thermochemical processes that convert wet biomass under certain pressure and temperature conditions into bio-coal, bio-oil and biogas, which are suitable for energetic and material applications [7]. HTP are classified as shown in Table 1:

Table 1
Classification of hydrothermal reactions (based on [8], updated with current data)

Hydrothermal reaction	Temperature [°C]	Pressure [bar]	Residence time	Main product	References
Hydrothermal carbonization (HTC)					
	190–230	10–30	30 min. up to several hours	Bio-coal/char	9, 10, 11
Hydrothermal liquefaction (HTL)					
Low temperature	220–250	40–200	Several minutes	Bio-oil	10, 12
High temperature	> 250–400	> 40–200	Several minutes	Bio-oil (usually higher yields than for low-temperature)	11, 13
Hydrothermal gasification (HTG)					
Sub-critical	280–374	< 221	Seconds up to several minutes	Mainly CH_4	8, 14, 15
Supercritical	> 374–800	> 221	Seconds up to several minutes	CH_4 at temperatures between 400-550 °C and H_2 at temperatures > 550 °C	14, 15
Aqueous phase reforming	200-280	15–50	Several hours	H_2, CO_2 and alkanes from oxygenates	8, 14

Unlike solid residues, wet biomasses require expensive pre-treatment processes (e.g., drying and thickening) before they are suitable for most biomass conversion processes [7], which is why simple and less costly treatment paths (e.g., combustion) are usually applied [16]. Regarding resource efficiency, such conversion paths are not optimal, because they do not exploit the complete energetic and material substrate potential [1].

Hence, HTP seems better suited to efficiently converting wet biomass into energy- and carbon-rich products. However, the technology has so far not been successful in Germany [17]. In a previous study [18], we identified opportunities and risks of HTP development in Germany. The benefits of HTP include the lower carbon footprint and higher energy efficiency of the processes compared to alternative methods (e.g., anaerobic digestion). Barriers arise due to a lack of experience in industrial continuous operation and constraints in the current legal framework (e.g., legal waste status of the solid product of HTC). We used these results to derive relevant key factors for HTP development in Germany until 2030 and their occurrence probabilities. Figure 1 gives an overview of the methodological process.

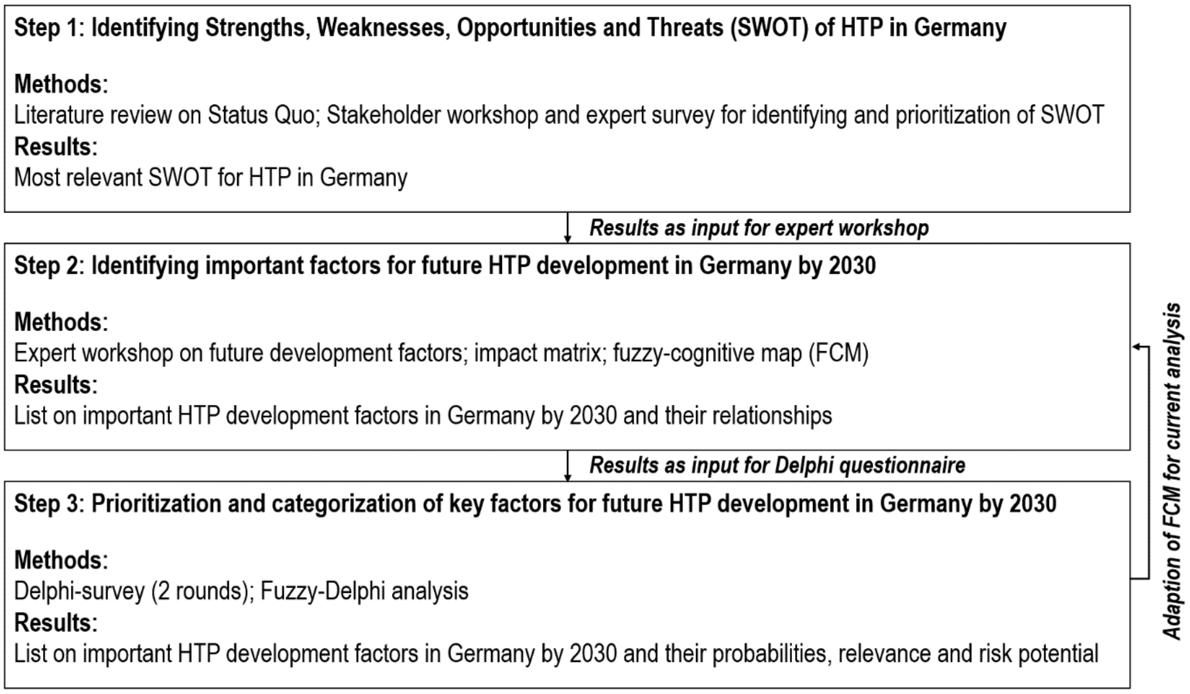

Fig. 1. Methodological steps to identify and categorize key factors for HTP development in Germany [adapted from 17]

The identification and categorization of the key factors was based on a SWOT analysis and expert workshop with impact analysis. From these analyses, a fuzzy cognitive map (FCM) was created (presented later in this study). Further, a Delphi survey with 51 European HTP experts was executed and evaluated using fuzzy-logic. Nevertheless, due to the qualitative nature of the methodology, uncertainties remain regarding the identified factors (e.g., regarding completeness, assessment of relevance and probability of occurrence). However, the authors' preparatory work is the only source of information of this kind; so far, no comparable research results have been available. Various feedback loops and the consistent use of information ensured that all relevant factors were identified and assessed as far as possible.

Based on the results of this process, a list of key factors for HTP development in Germany by 2030 resulted [17]. Table 2 summarizes the factors and provides information about the factors' estimated relevance for the future development of HTP (relevance of occurrence), risks in case of non-occurrence and probabilities of occurrence. Not all of the factors pose a development risk if they do not occur. In addition, some factors are not development drivers but rather risks. Corresponding factors are marked with asterisks and defined in the notes below the table.

Table 2
Important factors of HTP development in Germany [adapted from 17]

x_i	Tagging	Explanation	Relevance of occurrence	Risk in case of non-occurrence	Probability of occurrence
Political-legal factors					
x_1	Regular fuel recognition	HTP energetic products are recognized as standard fuels. This factor is strongly connected to the fourth factor as this represent an alternative requirement for the recognition of HTP products as standards fuels.	High	High	Uncertain
x_2	Investment and promotion	Investment incentives and / or technology and research funding programs for HTP are being introduced or rather promoted.	Uncertain	Uncertain	Low
x_3	“End of waste” regulation	An end-of-waste regulation is being introduced for HTP products (i.e. products from bio-waste etc.).	High	Uncertain	Uncertain
x_4	Product certification	Official recognition certificates for HTP products are introduced and issued accordingly by the competent authorities. This helps to reduce uncertainty for practice in terms of classification of HTP products as fuels.	Middle	Uncertain	Low
x_5	Thresholds	Thresholds relevant to HTP (e.g. Federal Pollution Control Act) are relaxed as far as reasonably possible.	Uncertain	Uncertain	Uncertain
x_6	Approval procedures	Approval procedures for new HTP plants are accelerated which might save costs during the planning and construction phase.	Uncertain	Uncertain	Uncertain
x_7	Product standardization	The quality of HTP products is standardized. This helps to reduce uncertainties on HTP product and sales markets (e.g. for product user) and enhances transparency.	Middle	High	Low
x_8	Substrate standardization*	The quality of HTP substrates is standardized. This helps to reduce uncertainties on HTP procurement markets (e.g. for substrate user) and enhances transparency.	Low	-	Low
x_9	Process standardization	Process standards are introduced. This helps to reduce uncertainties for plant constructers and operators and enhances transparency.	Low	Uncertain	Uncertain
Economic factors					
x_{10}	Sales markets	The competition on HTP relevant sales and product markets (e.g. energy carriers, fertilizers, substitutes for chemical products) decreases. Thus, the relative market share for HTP firms might be increase.	Low	Middle	Middle
x_{11}	Procurement markets	The competition on HTP relevant procurement markets (e.g. animal excreta, sewage sludge) decreases. Thus, more usable substrates for HTP might be available, also near to the plant location.	Uncertain	Middle	Uncertain

x_{12}	Substrate availability	The available and technically usable amount of substrates increases. Thus, in centralized concepts, plants might handle higher capacities. Or in decentralized concepts, more substrates will be available also near to the plant location assuming that substrate availability increases equally in Germany.	Low	Middle	High
x_{13}	Disposal costs	Disposal costs for HTP substrates per mass unit (e.g. ton) are increasing. Thus, revenues for dispose such substrates might also increases which would generate additional income for HTP plant operators.	Uncertain	Uncertain	High
x_{14}	Material applications*	HTP products are primarily used for material applications (e.g. as fertilizer, functional carbon). This could result if energy markets remain unprofitable due to legal barriers (missing recognition as regular fuels). Products for HTP might be primary applied on markets for bio-based products. However, this factors strongly depends on missing legal adjustments regarding fuel recognition according to expert opinions.	Uncertain	-	Uncertain
x_{15}	Foreign markets**	HTP plant manufacturer and operators concentrate almost exclusively on foreign markets. This might be a result of missing market demand, an insufficient or rather braking legal framework, low relative market shares for HTP products on related markets or missing political incentives and willingness on promoting HTP in Germany.	Uncertain	Uncertain	Uncertain
Technological factors					
x_{16}	Process water treatment	A cost-efficient and sustainable solution for process water treatment is being developed and applied nationwide. This might promote the overall economic (and ecological) performance of HTP as the polluted process water treatment is currently also a relevant cost (economic) factor which might make HTP concepts uneconomic.	Middle	Uncertain	High
x_{17}	System Integration 1*	HTP plants are increasingly being integrated into bio-waste and wastewater treatment facilities. Thus, the location of substrate occurrence and treatment facility could be integrated optimally which leads to lower logistic costs. Other synergies might be generated, e.g. process water treatment directly by the wastewater treatment plant on site.	High	-	Middle
x_{18}	System Integration 2*	HTP are increasingly being integrated into bio-refineries. This could also generate considerable synergies (e.g. cascade usage networks).	Uncertain	-	Middle
x_{19}	Nutrient recycling*	The nutrient recovery is enhanced. Especially, nutrient recovery from the process water might be promising as the process water must be treated anyway. Due to political and legal frameworks (2017 amendment of sewage sludge ordinance) that especially require phosphorus recovery from sewage sludge, this might be a useful strategy.	High	-	Uncertain

x_{20}	Learning effects	The process understanding and knowledge increases (learning effects, for example through reference systems / business cases). According to learning curve effect theory this will especially reduce costs per unit of product which is why therefore a techno-economic factor [19].	High	High	High
x_{21}	Accidents**	Accidents with existing facilities reduce trust in the safety of the technology. This might especially effect plant operator and society which is why this factor is strongly connected to social factors.	Uncertain	Uncertain	Uncertain
Ecological factor					
x_{22}	Life cycle performance*	Research on climate and resource protection by HTP will be intensified. Results on this also successively improve the life cycle performance due to new insights. This might especially promote social acceptance into the technology. However, the LC performance is strongly connected to several other factors (e.g. reduced pollutants in process water after treatment) which is why this factor is just one part of promoting the LC performance.	Uncertain	Uncertain	Uncertain
Social factors					
x_{23}	Customer acceptance	Customer acceptance of HTP increases. This might be the result due to technological progress, legal adjustments that promote HTP, higher transparency regarding HTP products quality (e.g. end-product customers), substrate quality and process performance (e.g. customer for facilities/plant operator).	Uncertain	Uncertain	Uncertain
x_{24}	Social acceptance	Social acceptance on HTP increase or rather society takes HTP as resource efficient technology for future biomass conversion stronger into account.	Uncertain	Uncertain	Uncertain

Explanation of asterisks:

* According to expert estimations, this factor is not considered as a risk if it not occurs. The corresponding field in the table is therefore filled with "-".

** According to expert estimations, this factor solely represents a risk. Hence, occurrence will have a negative effect.

Additional notes:

1) For the relevance, risks and probabilities of the factors that are described as "uncertain", no expert consensus was reached in the mentioned Delphi survey [cf. 17], which is why these factors estimations were classified as uncertain.

2) In the referenced study [17], the factors relevance and probabilities are classified by a ranking. In the present work, we use an easier understandable verbal classification based on this ranking, i.e. High (Rank 1-3), Middle (Rank 4-6), Low (Rank > 6).

3) The underlying ranking was created for each individual category using the fuzzy Delphi method, which is based on an expert Delphi survey among 51 European HTP experts. There were two rounds of surveys (1st round: 27 responses; 2nd round: 12 responses). For all categories (i.e. “Relevance of occurrence”, “Risk in case of non-occurrence”, “Probability of occurrence”,) the factors in the original questionnaire were assessed using a Likert scale from 1 (e.g. less relevant) to 5 (e.g. high relevant) assessed by the experts. The results were transferred to a fuzzy scale [cf. 20], evaluated by FDM and transferred to a ranking according to the result (see footnote 2). According to the questionnaire sent, the categories mentioned here are defined as follows:

- Relevance of occurrence: Events or factors that are considered to be particularly important, if the future development of HTP in Germany is to be pushed (e.g. construction of industrial plants).
- Risk in case of non-occurrence: Events or factors whose non-occurrence is considered to be particularly problematic, if the future development of HTP in Germany is to be pushed.
- Probability of occurrence: Events or factors that are estimated as particularly likely to occur by 2030.

Based on the information in Table 2, this work aims to map the system of factors and analyse their reaction on HTP scenarios, that are descriptions of possible future situations, combining a network of influencing factors. Scenarios depict possibilities and thus include a high degree of uncertainty in the assessment of future developments [21, 22, 23, 24]. To illustrate the contribution of the energetic use of biomass to the renewable energy system, for example, several scenario analyses have already been conducted in Germany [25, 26]. HTP has not been part of such studies. One reason is that the technology has not reached industrial maturity in Germany and therefore does not currently make any appreciable contribution to the renewable energy system. Nevertheless, a study by the German National Academy of Science and Engineering concludes that HTC and HTL could make an important contribution to the renewable energy system by 2023, closing the gap between combustion, gasification and pyrolysis and the microbiological processes [27].

Apart from the mentioned study, there is hardly any research into the future of HTP in Germany. Instead HTP research currently focuses on process optimization [28, 29] and techno-economic and ecological analyses [30, 31, 32]. Predictions are therefore dependent on many uncertainties and driven by various assumptions. A trend projection based on historical data is not possible for HTP, as there are insufficient data. Nevertheless, scenarios can be useful to learn more about the overall system behaviour and important factors and patterns. Additionally, they can reveal relationships and possible developments. Hence, the results of this study can help not only to produce recommendations for decision-makers in politics, science, industry and civil society, but also to identify “hidden patterns” and self-reinforcing feedbacks in the system.

2. Materials and Methods

2.1 Fuzzy cognitive maps for system modelling

The relationships and connections of the factors in Table 2 were modelled to illustrate the system relationships using FCM, which is a tool for representing the complex characteristics of non-linear dynamic systems, which may not be supported by a deterministic mathematical model [33]. Fuzzy signed graphs are used to model events and values as a collection of concepts (i.e., fuzzy sets that represent the factors), by forging a causal link between them [34, 35]. Due to their flexibility, adaptability and the intuitive way they are constructed, FCMs are increasingly used in various scientific disciplines [36, 37, 38] and are an important part of soft computing research [35]. An advantage of an FCM approach over hard computing approaches (e.g., system dynamics) is that it is tolerant of imprecision, uncertainty and approximation. Soft computing approaches such as FCM are well suited to handling highly complex (non-linear, multimodal, high-dimensional, etc.), poorly structured or ill-defined problems [39].

Another reason we decided to use this approach is that other studies have used FCMs to determine future technology development or have recommended them for this purpose. For example, Amer et al. applied FCMs to determine scenarios for the wind-energy sector in Pakistan to create a technology roadmap [40]. Jetter reviewed applications of FCMs and described them as being especially suitable for scenario planning and forecasting of technology trends [41].

A standard FCM is defined by a set of functions (X, W, C, f) [32, 34]:

- $X = \{x_1, x_2, \dots, x_n\}$, which represents the set of n concepts. They form the nodes of the graph.
- $W: (x_i, x_j) \rightarrow$ where w_{ij} is a function of $X \times X \; to \; K \rightarrow [-1,1]$ associating w_{ij} to a pair of concepts (x_i, x_j), with w_{ij} denoting a weight of directed edge (magnitude) from $x_i \; to \; x_j, if \; i \neq j$; otherwise, if w_{ij} is equal to zero, then $i = j$. Thus, $W \; (X \times X) = (w_{ij}) \in K^{n \times n}$ is an adjacency matrix, denoted in the following as A.
- $C: x_i \rightarrow C_i^{(t)}$ is a function that computes the activation degree $C_i \in \Re$ for each concept x_i referring to a discrete time $t = \{1, 2, \dots, T\}$.
- $f: \Re \rightarrow I$ represents the transfer function, which represents the multiple causal impacts on a specific concept for the previously defined activation period.

Depending on how the influence of one factor on the other is to be estimated, the weights w_{ij} are set differently:

- $w_{ij} > 0$, i.e., positive causality,
- $w_{ij} < 0$, i.e., negative causality,
- $w_{ij} = 0$, i.e., no causal relation.

We used pentavalent logic for the weightings' causalities with scalar values:

- −1: strong negative causality,
- −0.5: negative causality,
- 0: no causality,
- 0.5: positive causality,
- 1: strong positive causality.

To calculate the concept values in progress, the following formula is used as activation rule:

$$C_j^{(t+1)} = f\left(\sum_{\substack{i=1 \\ i \neq j}}^{n} C_i^{(t)} w_{ij}\right) \quad (1)$$

where n represents the number of concepts, $C_i^{(t)}$ describes the activation degree of concept x_i at the t-th time step, $C_j^{(t+1)}$ correspondingly represents the value of the concept C_j at the time $t + 1$ and w_{ij} represents the weighting of the causal connection of the corresponding concepts.

For the preparation of the FCM, we used information on the relationships between the factors from previous work [7, 11, 17, 18]. Based on this, we carried out an expert workshop which was attended by six German scientists working on HTP. In a moderated group discussion, all influencing factors were evaluated regarding their effects on one another and themselves using an impact analysis [20]. An impact matrix developed during the workshop was verified based on the information from the previous work. On that basis, the FCM adjacency matrix A was created.

2.2 Scenario construction and consistency check

The factors' relevance of occurrence, risks in case of non-occurrence and probabilities were used to construct the scenarios for HTP development in Germany. Scenario 1 incorporates the factors with high probability according to Table 2, scenario 2 incorporates the factors with high relevance of occurrence, and scenario 3 considers the probable factors, excluding those with a high risk in the event of non-occurrence. The combinations of factors were selected to reflect the most likely positive development (scenario 1), the most desirable development (scenario 2) and the most likely negative development (scenario 3).

To consider how independent the factors are in their appearance, the scenarios were checked for consistency. Consistency can range from total inconsistency (both projections never occur together) to absolute mutual support (both projections will most likely always coincide) [42]. For this check, a consistency matrix representing the impact values according to the FCM scalar values for the factor combinations was constructed. Table 3 shows the scale relations between the adjacency matrix and the consistency matrix.

Table 3
Scale adaption of FCM scale into consistency matrix scale

Consistency matrix linguistic meaning	Consistency scale	FCM scale
Total inconsistency: both projections never occur together.	1	not detectable

Partial inconsistency; i.e., the two projections influence each other. Their common occurrence affects the credibility of the scenario.	2	−0.5; −1
Neutral or independent of each other; i.e., the two projections do not affect each other and their appearance does not affect the credibility of the scenario.	3	0
Mutual benefit; i.e., the two projections may well occur in a scenario.	4	0.5
Very strong mutual support; i.e., due to the occurrence of the one projection, the occurrence of the other projection can be expected.	5	1

To identify whether the scenario combinations are consistent, we calculate average consistency values per scenario. For this, the following steps were performed:

(1) For every scenario, a consistency matrix $\boldsymbol{C}$ representing the degree of consistence was created.

(2) For every matrix, the relevant vectors $c_{ij}^{*} = \begin{pmatrix} c_{ij} \\ \cdots \\ c_{nj} \end{pmatrix}; i > j, i \in \mathbb{N}, i \in \mathbb{N}$ were selected and the average consistency per vector was calculated as $\overline{c_{ij}} = \frac{1}{n}\sum_{i=1}^{n} c_{ij}$ (2)

(3) Finally, the overall average per scenario was calculated as $\overline{cons} = \frac{\sum \overline{c_{ij}}}{n_j}$ (3)

The procedure described above is in part based on suggestions from [22]. An average consistency value ($\overline{cons}$) per scenario which is close to 3 indicates that the factor combinations are consistent. If no consistency is reached, the adjacency matrix may be adapted because it serves as the basis for the consistency matrix.

2.3 Scenario-based system analysis

Following the steps in sections 2.1 and 2.2, the scenarios were applied to the FCM to show how the system reacts. To illustrate the system reaction for each scenario, the factors can be set at a value between +1 (strong positive concept change) and −1 (strong negative concept change). Within this analysis, a strong impact (+1) was distinguished from a less strong impact (+0.5). Negative concept change was not applied, as all scenarios assume a positive concept change. The relative change in the system was displayed through a bar graph indicating how the system might react in a given scenario. We used the sigmoid function to generate the variations of concepts, because many complex systems show a progression from small values at the start that accelerate and approach a peak. It is usual for such system assessments to use sigmoid functions if an explicit mathematical model is absent [42]. Additionally, sigmoid FCMs are well suited to qualitative problems that require evidence of the increase, decrease or stability of a concept, especially for strategic decisions based on scenarios [43], which is the case for this study. The system factor dynamics were calculated as follows [44]:

(1) An adjacency matrix A was created representing the concepts' interconnections and intensity of causal interrelations:

$$A = \begin{array}{c c} & \begin{array}{ccc} x_1 & & x_m \end{array} \\ \begin{array}{c} x_1 \\ \\ x_n \end{array} & \begin{pmatrix} w_{11} & \cdots & w_{1m} \\ \vdots & \ddots & \vdots \\ w_{n1} & \cdots & w_{nm} \end{pmatrix} \end{array} \tag{4}$$

(2) The initial vector state was denoted as follows:

$$\vec{X}^0 = (x_1{}^o \; x_2{}^o \; \ldots \; x_n{}^o) \tag{5}$$

(3) The scenario-based values of the concepts (initial state changes) were calculated with an activation function ($f\ (x)$), in this case the sigmoid function. For this, the initial concept states were varied according to the corresponding scenario:

$$\vec{X}^{t+1} = f\left(\vec{X}^{t+1} * A\right) = (x_1{}^{t+1} \;\; x_2{}^{t+1} \;\; \ldots \;\; x_n{}^{t+1}) \tag{6}$$

(4) The state changed throughout the processes. The inference process stopped when stability was reached. The final vector state showed the effect of concept changes on the whole system of concepts.

3. Results

3.1 FCM for HTP system factors

Based on the process presented in Figure 1, we created the following adjacency matrix A that represents the interconnections of the concepts. The matrix is based on assessments from the expert workshop in which six HTP experts from the German Biomass Research Centre and the corresponding author participated (cf. Fig. 1). In the workshop, the participants assessed the causalities between the individual factors qualitatively. Based on this, an impact matrix was created, which was finally transferred to the adjacency matrix shown in Table 4. Further details are described in [17].

Table 4
Adjacency matrix: FCM factors and concepts relationships according to expert knowledge and relevant literature [own presentation]

x_{ji}	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}
x_1	0	1	1	-1	1	1	1	0	0	-0.5	0	-0.5	-0.5	-0.5	-0.5	1	0	0	0	0	-0.5	0	0.5	1
x_2	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0.5	0.5	0	0.5	0	0	0	0
x_3	1	0	0	-1	1	0.5	0.5	0.5	0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	1	0	0	0	0	0	0.5	0.5	1
x_4	-1	0	-1	0	1	1	1	0	0	0	-0.5	0	-0.5	-0.5	-0.5	0.5	0	0	0	0	0	0	0	1
x_5	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x_6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0.5	0.5	0	0	0	0	0.5	0
x_7	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5
x_8	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0.5	0	0	0	0	0	0.5	0.5	0.5
x_9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5	-0.5	0	0.5	0.5
x_{10}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0.5	0	0	0	0.5	0
x_{11}	0	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0	0	0	0	0
x_{12}	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0	0	0	0	0	0	0	0
x_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
x_{14}	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0.5
x_{15}	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
x_{16}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5
x_{17}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0	0.5	1	0	0	0.5	0.5	0.5
x_{18}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	0	0	0.5	0	1	0	0	0.5	0.5	0.5
x_{19}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	1	0.5	0.5
x_{20}	0	0	0	0	0	0.5	0	0	0.5	0	0	0	0	0	-0.5	0	0	0	0	0	0	0.5	1	0.5
x_{21}	0	0	0	0	0	-0.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0	-0.5	0	0	-1	-1
x_{22}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5

x_{23}	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
x_{24}	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

The FCM also represents these interconnections, but in a visualized form. The map was created with the online software Mental Modeler [45]. For transparency reasons, we appended a description of how the model can be rebuilt based on the adjacency matrix using Mental Modeler (see Appendix).

To give an impression of the complexity of the FCM, Figure 2 shows a part of the map for political-legal concepts. We decided to show this part of the FCM because the political-legal concepts have the highest impact of all the concepts on the overall system [45, 46, 47].

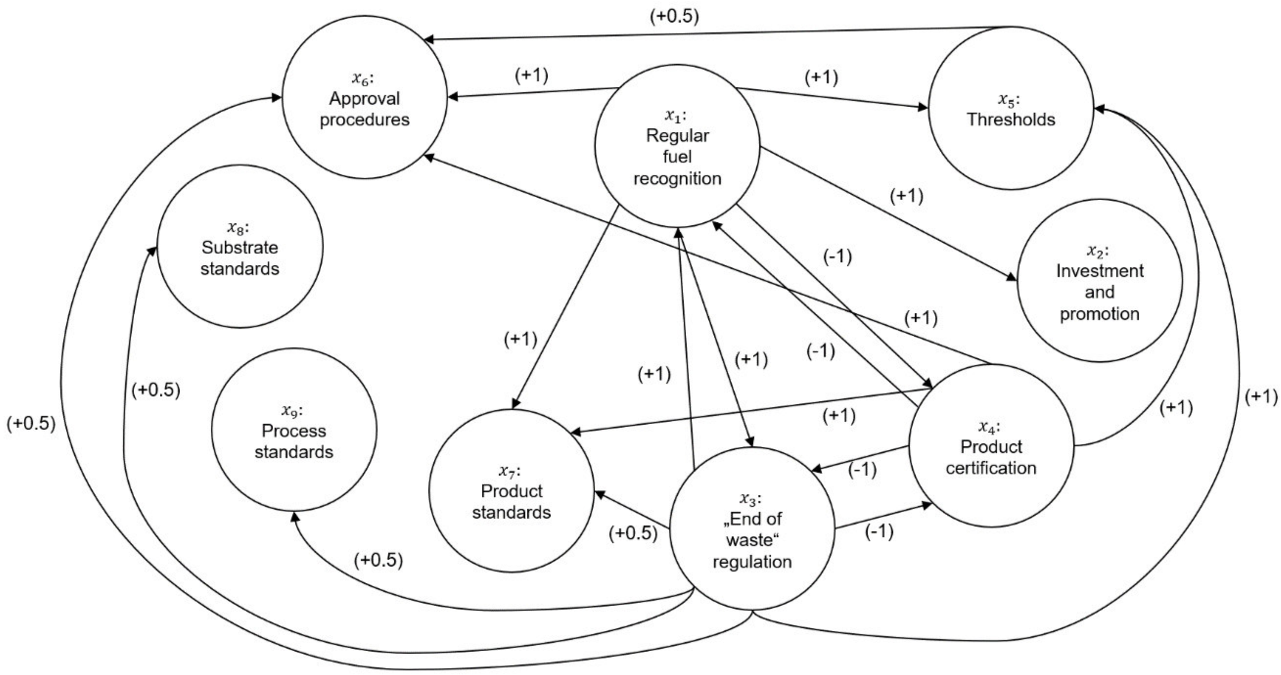

Fig. 2. FCM based on expert knowledge for political-legal concepts (own presentation)

The numerical values represent the weight w_{ij} of the directed edge of each concept pair. It can be seen that "Regular fuel recognition" in particular has a strong influence on other concepts, indicated by the various relations marked "+1". In general, the occurrence of this concept positively influences other system concepts. The weight "0", which represents no causal relation between the concepts, is not visualized.

3.2 HTP development scenarios by 2030

Based on the methodology described in section 2.2, the scenarios presented in Table 5 were created.

Table 5
HTP scenarios for Germany by 2030

HTP Scenario	Scenario factor combination and description
Technological Action $\overline{cons} \approx 3$ Consistent	$Factor\ combination = \{x_{12};\ x_{13};\ x_{16};\ x_{20}\}$ The available and usable amount of substrates increases (x_{12}). Disposal costs for HTP substrates (e.g., sewage sludge) are increasing (x_{13}). A cost-efficient and sustainable solution for process-water treatment is being applied (x_{16}) and in general, learning effects can be observed (x_{20}).
Legal and Technological Action $\overline{cons} \approx 3.3$ Nearly consistent	$Factor\ combination = \{x_1;\ x_3;\ x_{17};\ x_{19};\ x_{20}\}$ HTP energetic products are recognized as standard fuels, largely based on an end-of-waste regulation for HTP products ($x_1;\ x_3$). HTP plants are increasingly being integrated into bio-waste and wastewater treatment facilities (x_{17}). The nutrient recovery is enhanced (x_{19}), and, in general, learning effects can be observed (x_{20}).
No Action $\overline{cons} \approx 3.2$ Nearly consistent	$Factor\ combination = \{x_{12};\ x_{13}\}$ The available and usable amount of substrates increases (x_{12}). Disposal costs for HTP substrates (e.g., sewage sludge) are increasing (x_{13}). Although the risk in non-occurrence of an efficient process water-treatment is rated as uncertain, we excluded this factor here, because, based on discussions with experts, we see this as a serious risk. Learning effects are excluded, as their non-occurrence is seen as a serious risk.

The respective factor combinations indicate which of the factors listed in Table 2 occur in the respective scenario. The first scenario includes mostly technological changes, and so it is referred to as the "technological action" (TA) scenario. The second scenario includes also legal changes and is thus named the "legal and technological action" (LTA) scenario. The substrate and disposal cost increases are factors that are not directly influenced by specific actions, which is why the last scenario is named the "no action" (NA) scenario.

As mentioned in section 2, when considering the system reactions, we distinguish between strong (+1) and weak (+0.5) impacts of the factors. It should be noted that for factors that either occur or fail to occur, no distinction can be made between strong and weak impacts. In this study, this point concerns only the legal framework conditions, as these are either introduced or not; we cannot make a substantiated distinction between weak and strong impacts in the legal framework conditions.

The following matrices were used to calculate the average consistency value for each scenario (cf. $\overline{cons}$ in Table 5) according to formulas (2) and (3).

$$C_{probable} = \begin{array}{c c} & \begin{array}{cccc} x_{12} & x_{13} & x_{16} & x_{20} \end{array} \\ \begin{array}{c} x_{12} \\ x_{13} \\ x_{16} \\ x_{20} \end{array} & \begin{pmatrix} 3 & 4 & 3 & 3 \\ 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 \end{pmatrix} \end{array}$$

$$C_{relevance} = \begin{array}{c c} & \begin{array}{ccccc} x_{1} & x_{3} & x_{17} & x_{19} & x_{20} \end{array} \\ \begin{array}{c} x_{1} \\ x_{3} \\ x_{17} \\ x_{19} \\ x_{20} \end{array} & \begin{pmatrix} 3 & 5 & 3 & 3 & 3 \\ 5 & 3 & 3 & 3 & 3 \\ 3 & 3 & 4 & 5 & 3 \\ 3 & 3 & 3 & 3 & 3 \\ 3 & 3 & 3 & 3 & 3 \end{pmatrix} \end{array}$$

$$C_{risk} = \begin{array}{c c} & \begin{array}{cc} x_{12} & x_{13} \end{array} \\ \begin{array}{c} x_{12} \\ x_{13} \end{array} & \begin{pmatrix} 3 & 4 \\ 3 & 3 \end{pmatrix} \end{array}$$

3.3 FCM system reaction to scenarios

We want to emphasize once again that the analysis is semi-quantitative and the results are primarily based on expert knowledge and not on quantitative data. The quantification step uses the mathematical procedure of the FCM explained in section 2. It should be noted that the variations represent corresponding changes until 2030, and some factors do not refer to the actual state. This is because certain factors are currently not observable. Figure 3 shows the system reaction per scenario.

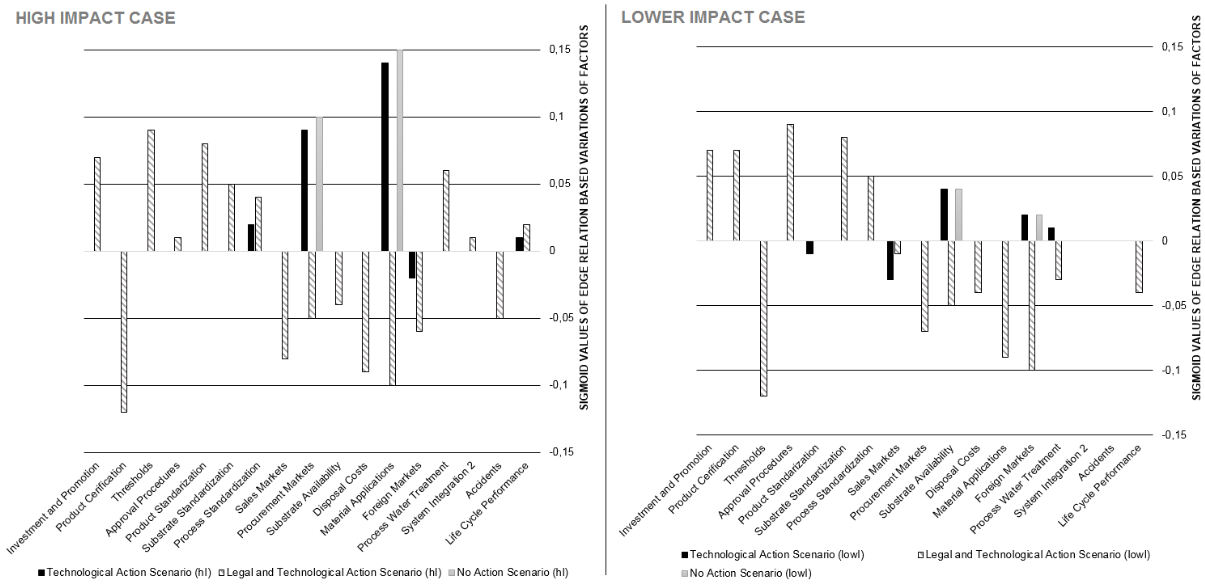

Fig. 3. FCM system factors variations for each HTP scenario assuming high factor (hI) and lower factor (lowI) impact.

* For factors that are not listed (e.g., x_1; x_3; x_{19}; x_{20}), the change is "0" for all variants and scenarios, which is why they are not included in the figures.

4. Discussion

4.1 Interpretation of system reaction to scenarios

The TA (hI) scenario has a relatively small impact on the system and affects just five factors. Thus, the system generally reacts robustly to this scenario, which suggests a stable development that, apart from the scenario factors and the factors influenced, corresponds to the status quo. The economic factors show the strongest reactions. The competition in the procurement markets is decreasing, which can be explained by the increasing amount of substrates. Due to the assumed largely positive technological development and the decreasing production costs per unit reasoned in the assumed learning effects, the willingness of the actors to concentrate on foreign markets is decreasing. However, this effect is quite small, as there is still a rather restrictive legal framework in Germany, that still hinders the energetic use of HTP products as standard fuels.

In the NA (hI) scenario, there are very few changes to the status quo, which is due to the fact that only two scenario factors occur. The competition in the procurement markets tends to decline, which is due to the increasing amount of substrate. The development of HTP according to this scenario is stagnant.

The greatest number of effects can be observed in the LTA scenario. This is mainly due to the high impact of the assumed legal adjustments. As can be seen in Figure 2, "regular fuel recognition" has a high impact on the overall system and influences several factors directly. Approval of HTP products as energetic products provides legal certainty regarding energy use, which could have various effects. For example, the likelihood of investment and technology funding could increase, and the market for material applications could become less attractive as the energy market is now fully accessible for HTP products. Furthermore, the approval of HTP products as a standard fuel makes product certification largely obsolete, which is reflected in the negative value of this factor. The competitive situation in the procurement and sales markets is therefore exacerbated by the likely increase in the number of actors in the HTP branch. Foreign markets also lose their appeal as a result of the supporting legal framework. As HTP development gathers momentum, standardization processes could become more frequent. Planning and approval procedures could be also simplified. Technological development could also increase, probably due to development dynamics, as evidenced by the high likelihood of introducing a cost-effective process-water treatment.

In the LTA (lowI) scenario, the difference to the high-impact case is very small, because it is still assumed that the legal changes are introduced. This clearly shows the high relevance of the legal factors.

In the NA (lowI) scenario, the same system factors react as in the high-impact case, albeit with a much lower severity. The strength of the scenario factors therefore disproportionately affects the system factors in this scenario.

Most of the differences between high and low-impact cases appear in the TA scenario. In the lower-impact case, for example, the probability of occurrence of process standards is reduced, which may be due to the less pronounced learning effects and technological advances in process-water treatment. As technological advances are less pronounced, it may be more difficult to achieve uniform process standards based on generally accepted best available techniques. This difficulty is also reflected in the fact that the factor "approval procedures" shows a negative value, and so it is less likely that approval procedures will be simplified in this scenario. Interestingly, the factor “foreign markets” has a positive value. The lower factor impact in this scenario is not enough to reduce the interest of the branch in foreign markets.

4.2 Comparison of results for Germany with those of other countries

To the authors’ knowledge, there are no comparable studies for other countries. Nevertheless, some literature is available on current development potential and obstacles outside Germany. For example, [48] mentioned the potential for HTC in Europe as an innovative technology for the production of growing-media alternatives (e.g., peat). However, the study does not make a detailed assessment of other potentials and obstacles. [49] discussed future perspectives of hydrothermal conversion for the production of fuels and energy carriers, but without a geographical focus. In their opinion, the technology has reached industrial maturity; however, research into suitable and stable catalysts and handling of the liquid phase from HTC and HTL, for example, is still necessary for economic feasibility. [50] analysed the suitability of HTC for food waste treatment in China and recommended to use it for this purpose combined with anaerobic digestion.

The results of the studies mentioned are consistent in individual points with the present study. However, the mentioned studies do not consider an overall system of factors. For international readers, this study can provide first hints about potentials and obstacles, because many factors apply not only to Germany. The legal problem of fuel approval applies to the whole of Europe. In addition, the central techno-economic problems and potentials apply beyond Germany (e.g., treating the process water).

4.3 Limitations of this work and suggestions for further research

This study is mainly based on expert knowledge and thus on qualitative information. This is because there is little reliable historical data for the development of the relevant system factors. Deterministic models, which mathematically describe the relationship of the factors to one another, do not exist. Previous studies have shown that the FCM is a method well-suited for such analyses as it does not require quantitative inputs and can provide helpful results based on qualitative descriptions and relationships. Although the results are largely based on qualitative expert assessments, through the broad participation process and the evaluation and analysis of information using fuzzy logic, they can be seen as reliable.

The main contribution of this study is the systematic creation and comparison of different development paths for HTP until 2030. This contribution can help decision-makers in business, science, politics and civil society to identify bottlenecks for HTP in Germany. Future studies could expand the system by including new factors that could be identified by further expert knowledge. The relationships between the factors can be updated based on potential new information. In addition, other scenarios (i.e., factor combinations) could also be considered with regard to their effect on the system to identify further correlations. Future studies should at least partially elaborate deterministic models and validate them with available data, as far as possible and reasonable.

5. Conclusion and Recommendations

The purpose of this study was to comprehensively map the system of factors in scenarios of HTP in Germany and analyse their reactions. This is unique because it attempts to describe the complete system of factors for the future development of HTP in Germany and their interactions. The study supports previous analysis of the with further findings.

The legal factors have a large influence on the system. Based on this analysis, approval of HTP products as regular fuels is a prerequisite for creating legal certainty for the energetic use of the products. The model shows that this legal certainty in turn has various effects; for example, product certifications are less necessary, foreign markets lose relevance for domestic companies, technology funding and the establishment of substrate and process standards is more likely. A recommendation of this study is therefore that HTP products should be legally recognized as products, because the positive effects for the development of the technology are significant. Specifically, in EU or national waste law the legislator could specify the so named “End of waste” status of HTP products according to Article 6 Waste Framework Directive.

Techno-economic factors (e.g., efficient process-water treatment, nutrient recycling, learning effects) also have an impact on the overall system, but less than the legal factors, which is shown by the different reactions in the TA and LTA scenarios. Nevertheless, these factors are also important for the development of HTP and they are to be implemented in conjunction with the legal factors. Hence, also technology funding is recommended, including the development of a cost-efficient process-water treatment, integrated approaches such as nutrient recycling, and the supporting of the construction of the facilities in industrial continuous operation in Germany.

The methodological framework and analysis presented in this paper can support policy-makers regarding legislation and technology funding. The results are also useful for science because they allow for an improved prioritization of research.

The value added by this study lies in the fact that development paths for HTP were derived, the system effects were analysed through FCM analysis and thus the understanding of the system was increased. The influencing factors were previously known and prioritized, but their effects on one another had not been analysed. It is critical to note that the analysis does not offer objective accuracy and is based not on quantitative data but on qualitative expert statements. Nevertheless, the study presents trends and their effects, which can support future decisions.

Funding

This work was supported by the Helmholtz Association under the Joint Initiative "Energy System 2050 - A Contribution of the Research Field Energy".

Acknowledgements

We are grateful to all experts, who have supported us within the various participation formats. Special thanks to the scientists of the German Biomass Research Centre (DBFZ) for taking part in the scenario/expert workshop. Additionally, we want to thank the anonymous reviewers and the editor for their very helpful and constructive hints and comments on our manuscript.

Appendix

Short manual for rebuilding the fuzzy-logic cognitive map and calculate the system reactions:

1. Visit the website www.mentalmodeler.com.
2. Create a login as described on the website.
3. After you have access to the tool, activate your Flash Player.
4. In the "Model" tab, enter all the factors listed in Table 1 (as boxes). The program automatically assigns "fuzzy set" values.
5. Then switch to the tab "Matrix" and enter the values for the connections between the factors acc. Table 4.
6. Then go to the tab "Scenario" and create the scenarios acc. Table 5. Select "sigmoid" as the calculation form.
7. Now vary between high impact (+1) and lower impact (+0.5) cases.
8. Mental Modeler will now give you the scenario values that should match with Figure 3.

References

[1] F. Baur, Effiziente Nutzung von Biomasse – Reststoffe, Nutzungskonkurrenzen und Kaskadennutzung. FVEE-Themen (2010) 88-92.

[2] K. Fricke, T. Bahr, O. Kugelstadt, C. Heußner, S. Scholl, E. Kraft, K. Bidlingmaier, D. Meier-Kohlstock, T. Haupt, M. Meiller, F. Stenzel, Steigerung der Energieeffizienz in der Verwertung biogener Reststoffe. German research programme biomass energy use, 2012. doi: 10.2314/GBV:773389504.

[3] A. Bezama, P. Agamuthu Addressing the big issues in waste management. Waste Management & Research 37(1S) (2019) 1-3.

[4] A. Bezama, Understanding the systems that characterise the circular economy and the bioeconomy. Waste Manage. Res. 36 (7) (2018) 553 – 554.

[5] C. Ingrao, J. Bacenetti, A. Bezama, V. Blok, P. Goglio, E.G. Koukios, M. Lindner, T. Nemecek, V. Siracusa, A. Zabaniotou, D. Huisingh, The potential roles of bio-economy in the transition to equitable, sustainable, post fossil-carbon societies: Findings from this virtual special issue. J. Clean Prod. 204 (2018) 471 – 488.

[6] A. Bezama, Let us discuss how cascading can help implement the circular economy and the bio-economy strategies. Waste Manage. Res. 34 (7) (2016) 593 – 594.

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

[8] M.K. Hrncic, G. Kravanja, Z. Knez, Hydrothermal treatment of biomass for energy and chemicals. Energy 116 (2016) 1312-22. doi: 10.1016/j.energy.2016.06.148.

[9] H.E. Putra, E. Damanhuri, K. Dewi, A.D. Pasek, Hydrothermal carbonization of biomass waste under low temperature conditions. MATEC Web of Conferences 154(01025) (2018) 1-5. doi: 10.1051/matecconf/201815401025.

[10] H. Simsir, N. Eltugral, S. Karagoz, Hydrothermal carbonization for the preparation of hydrochars from glucose, cellulose, chitin, chitosan and wood chips via low-temperature and their characterization. Biores. Techn. 246 (2017) 82-87. doi: 10.1016/j.biortech.2017.07.018.

[11] D. Reißmann, D. Thrän, A. Bezama, How to identify suitable ways for the hydrothermal treatment of wet bio-waste? A critical review and methods proposal. Waste Management Research 36(10) (2018) 912-923. doi: 10.1177/0734242X18785735.

[12] Y. Zhang, J. Minaret, Z. Yuan, A. Dutta, C. Xu, Mild Hydrothermal Liquefaction of High Water Content Agricultural Residue for Bio-Crude Oil Production: A Parametric Study. Energies 11(11) (2018) 3129. doi: 10.3390/en11113129.

[13] F. Qian, X. Zhu, Y. Liu, Q. Shi, L. Wu, S. Zhang, J. Chen, Z.J. Ren, Influences of Temperature and Metal on Subcritical Hydrothermal Liquefaction of Hyperaccumulator: Implications for the Recycling of Hazardous Hyperaccumulators. Environ. Sci. Technol. 52(4) (2018) 2225-2234. doi: 10.1021/acs.est.7b03756.

[14] V.R. Paida, D.W.F. Brilman, S.R.A. Kersten, Hydrothermal gasification of sorbitol: H2 optimisation at high carbon gasification efficiencies. Chem. Engineering J. 358 (2019) 351-361. doi: 10.1016/j.cej.2018.10.008.

[15] S. Nanda, S.N. Reddy, D.N. Vo, B.N. Sahoo, J.A. Kozinski Catalytic gasification of wheat straw in hot compressed (subcritical and supercritical) water for hydrogen production. Energy Science & Engineering 6(5) (2018) 448-459. doi: 10.1002/ese3.219.

[16] B. Wiechmann, C. Dienemann, C. Kabbe, S. Brandt, I. Vogel, A. Roskosch, Sewage sludge management in Germany. Umweltbundesamt (UBA), Dessau-Roßlau, 2013.

[17] D. Reißmann, D. Thrän, A. Bezama, Key Development Factors of Hydrothermal Processes in Germany by 2030: A Fuzzy Logic Analysis. Energies 11(12) (2018) 3532.

[18] D. Reißmann, D. Thrän, A. Bezama, Techno-economic and environmental suitability criteria of hydrothermal processes for treating biogenic residues: A SWOT analysis approach. J. Clean. Prod. 200 (2018) 293-304. doi: 10.1016/j.jclepro.2018.07.280.

[19] A.C. Hax, N.S. Majluf, Competitive cost dynamics: The experience curve. Interfaces 12 (1982) 50-61.

[20] S. de la Rosa de Sáa, M. Ángeles Gil, M.T. López García, M. Asunción Lubiano, Fuzzy Rating vs. Fuzzy Conversion Scales: An Empirical Comparison through the MSE. Synergies of Soft Computing and Statistics for Intelligent Data Analysis 190 (2013) 135-143.

[21] J. Gausemeier, A. Fink, O. Schlake, Szenario-Management: Planen und Führen nach Szenarien. Munich, Vienna, Germany, Austria. 2nd ed., 1996.

[22] K. van der Heijden, Scenarios. The Art of Strategic Conversation. John Wiley & Sons, Chichester, 1996.

[23] H. Kosow, R. Gaßner, Methoden der Zukunfts- und Szenarioanalyse: Überblick, Bewertung und Auswahlkriterien. IZT Werkstattbericht Nr. 103, Berlin, Germany, 2008.

[24] C. Varum, C. Melo, Directions in scenario planning literature – A review of the past decades. Futures 42(4) (2010) 355-369. doi: 10.1016/j.futures.2009.11.021.

[25] N. Szarka, M. Eichhorn, R. Kittler, A. Bezama, D. Thrän, Interpreting long-term energy scenarios and the role of bioenergy in Germany, Renew. Sustain. Energ. Rev. 68(2) (2017) 1222-1233. doi: 10.1016/j.rser.2016.02.016.

[26] A. Fritzsche, U. Kluge, M. Reiner, S. Thieme-Czach, Gutachten EE-Ausbaupotentiale in Sachsen. Study of the Federal State of Saxony, Dresden, Germany, 2018.

[27] E. Weidner, P. Elsner, Bioenergie: Technologiesteckbriefe zur Analyse “Flexibilitätskonzepte für die Stromversorgung 2050”. Schriftenreihe Energiesysteme der Zukunft. Berlin, Munich, Germany, 2016.

[28] E. Danso-Boateng, G. Shama, A.D. Wheatley, S.J. Martin, R.G. Holdich, Hydrothermal carbonisation of sewage sludge: Effect of process conditions on product characteristics and methane production. Bioresource Tech. 177 (2015) 318-327. doi: 10.1016/j.biortech.2014.11.096.

[29] J. Zhang, Y. An, A. Borrion, W. He, N. Wang, Y. Chen, G. Li, Process characteristics for microwave assisted hydrothermal carbonization of cellulose. Bioresour. Tech. 259 (2018) 91-98. doi: 10.1016/j.biortech.2018.03.010.

[30] X. Liu, B. Saydah, P. Eranki, L.M. Colosi, B.G. Mitchell, J. Rhodes, A.F. Clarens, Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction. Bioresour. Tech. 148 (2013) 163-171. doi: 10.1016/j.biortech.2013.08.112.

[31] J.S. Luterbacher, M. Fröling, F. Vogel, F. Marechal, Tester, J.W. Hydrothermal Gasification of Waste Biomass: Process Design and Life Cycle Assessment. Environ. Sci. Technol. (2009) 43 1578-1583. doi: 10.1021/es801532f.

[32] J. Medick, I. Teichmann, C. Kemfert, Hydrothermal carbonization (HTC) of green waste: An environmental and economic assessment of HTC coal in the metropolitan region of Berlin, Germany. DIW Discussion Papers, No. 1690, Deutsches Institut für Wirtschaftsforschung (DIW), Berlin, Germany, 2017.

[33] E. Yesil, C. Ozturk, M.F. Dodurka, A. Sakalli, Fuzzy cognitive maps learning using Artificial Bee Colony optimization. Proceedings of the IEEE International Conference on Fuzzy Systems (2013). doi: 10.1109/FUZZ-IEEE.2013.6622524.

[34] B. Kosko, Fuzzy cognitive maps. International Journal of Man-Machine Studies 24(1) (1986) 65-75. doi: 10.1016/S0020-7373(86)80040-2.

[35] G. Felix, G. Napoles, R. Falcon, W. Froelich, K. Vanhoof, R. Bello, A review on methods and software for fuzzy cognitive maps. Artif Intell Rev (2017) 1-31. doi: 10.1007/s10462-017-9575-1.

[36] J. Aguilar, A Survey about Fuzzy Cognitive Maps Papers. International Journal of Computational Cognition 3(2) (2004) 27-33.

[37] E.I. Papageorgiou, J.L. Salmeron, A Review of Fuzzy Cognitive Maps Research During the Last Decade. IEEE Transactions on Fuzzy Systems 21(1) (2012) 66-79. doi: 10.1109/TFUZZ.2012.2201727.

[38] L.G. Zanon, L.C.R. Carpinetti, Fuzzy Cognitive Maps and Grey Systems Theory in the Supply Chain Management Context: a literature review and a research proposal. Proceedings of the 2018 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE) (2018). doi: 10.1109/FUZZ-IEEE.2018.8491473.

[39] V.A. Niskanen, Soft Computing Methods in Human Sciences. Springer, Berlin, 2004.

[40] M. Amer, T. Daim, A.J. Jetter, Technology roadmap through fuzzy cognitive map-based scenarios: the case of wind energy sector of a developing country. Technology Analysis and Strategic Management 28(2) (2015), 1-25.

[41] A.J. Jetter, Fuzzy Cognitive Maps for Engineering and Technology Management: What Works in Practice? Technology Management for the Global Future PICMET 2 (2006), 498-512. doi: 10.1109/PICMET.2006.296648

[42] M.N. Gibbs, Variational Gaussian process classifiers. IEEE Transactions on Neural Networks 11(6) (2000) 1458–1464. doi:10.1109/72.883477.

[43] M. Leon, C. Rodriguez, M.M. Garcia, R. Bello, K. Vanhoof, in: Sidorov G et al. (Eds.), Fuzzy Cognitive Maps for Modeling Complex Systems, MICAI 2010, Part I, LNAI 6437 166 – 174, Springer-Verlag, Berlin, Heidelberg, 2010.

[44] J.L. Salmeron, R. Vidal, A. Mena, Ranking Fuzzy Cognitive Maps based scenarios with TOPSIS. Expert Systems with Applications 39(3) (2012) 2443-2450. doi: 10.1016/j.eswa.2011.08.094.

[45] S.A. Gray, S. Gray, L.J. Cox, S. Henly-Shepard, Mental Modeler: A Fuzzy-Logic Cognitive Mapping Modeling Tool for Adaptive Environmental Management. Proceedings of the 46th Hawaii International Conference on System Sciences (2013). doi: 10.1109/HICSS.2013.399.

[46] U. Özesmi, S.L. Özesmi, Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. Ecological Modelling 176(1-2) (2004) 43-64. doi: 10.1016/j.ecolmodel.2003.10.027.

[47] C. Eden, F. Ackerman, S. Cropper, The analysis of cause maps. J. Manage. Stud. 29 (1992) 309-323. doi: 0022-2380 $3.50.

[48] N. Gruda, Current and Future Perspective of Growing Media in Europe, Acta horticulturae 960(960) (2012), 37-43. doi: 10.17660/ActaHortic.2012.960.3.

[49] A. Kruse, A. Funke, M.M. Titrici, Hydrothermal conversion of biomass to fuels and energetic materials, Current Opinion in Chemical Biology 17(3) (2013), 515-521. Doi: 10.1016/j.cbpa.2013.05.004.

[50] Y. Zhou, N. Engler, M. Nelles, Symbiotic relationship between hydrothermal carbonization technology and anaerobic digestion for food waste in China, Bioresource Technology 260 (2018), 404-12. Doi: 10.1016/j.biortech.2018.03.102.