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Analysis

Learning to change: Transformative knowledge for building a sustainable bioeconomy

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ABSTRACT

The transition towards a bioeconomy is considered a powerful approach to combating current trends of unsustainability. To date, the concept has been widely perceived as a predominantly technical endeavor. This is, however, not sufficient and will not really tackle the global sustainability challenges. Therefore, the imparting of technological knowledge must be accompanied by instruction in other types of knowledge, particularly transformative knowledge. The authors explore the various elements of transformative knowledge necessary to equip the protagonists of a bioeconomy transformation. On this basis, four academic bioeconomy programs across Europe are analyzed using a hybrid methodological approach, combining a keyword-based content analysis of the module descriptions with semi-structured interviews of key representatives of the programs. It is shown that the syllabi of all four programs include important elements of transformative knowledge, such as communication, participation, and decision making skills. Skills related to the ability to revise and reflect personal values, in contrast, are mainly only an implicit part of the program. The study applies insights into education for sustainable development to the requirements of a fundamental transformation towards a sustainable bioeconomy. It offers a first appraisal of the consideration transformative knowledge is given in the design of European academic bioeconomy curricula.

1. Introduction

Around the world, governments are developing strategies to confront current global challenges – climate change, the over-exploitation of natural resources associated with the depletion of the natural environment, or issues of malnutrition and poverty. Continuing our current modes of consumption and production will lead to a situation in which the stability of the Earth System can no longer be guaranteed (Steffen et al., 2015). It has been repeatedly argued that “business as usual” is no longer an option (Leach et al., 2012). A relatively novel and currently strongly endorsed approach to overcoming some of the imminent challenges is the establishment of a bioeconomy - an economy based on innovative methods to substitute fossil resources with the intelligent and efficient use of bio-based materials and processes. Policies and strategies to foster the bioeconomy are being given priority on a number of political levels (EC, 2012; Federal Ministry for Food and Agriculture, 2014; MWK, 2013; Rönnlund et al., 2014). The aim of the European bioeconomy strategy is „to pave the way to a more innovative, resource efficient and competitive society that reconciles food security with the sustainable use of biotic renewable resources for industrial purposes, while ensuring environmental protection” (EC, 2012, p. 2). In a similar vein, the German government claims that the bioeconomy is a tool to overcome the challenges of the future (Federal Ministry of Education and Research, 2017), while Finland expects their bioeconomy to reduce their “dependence on fossil natural resources, prevent biodiversity loss and create new economic growth and jobs in line with the principles of sustainable development” (Finnish Ministry of Employment and the Economy, 2014, p. 3).

None of these framings leaves a doubt that the bioeconomy is an important means to combatting global challenges such as climate change, food security, and the depletion of natural resources. The logic appears to be quite simple: substituting fossil resources with renewable resources and biological processes and optimizing their cultivation by means of technological innovation will reduce CO_2 emissions and at the same time guarantee a sufficient supply of resources for food, energy and material production. Yet for a bioeconomy to contribute to overcoming currently unsustainable practices, relevant innovations must involve more than alternative raw materials and new technologies.

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Instead, systemic innovations on multiple levels are required (Federal Ministry of Education and Research, 2014; MWK, 2013): We need a pervasive transformation encompassing the dynamics and complementarities of technological, organizational, economic, institutional, socio-cultural, political, and environmental systems (Leach et al., 2010; Schlaile et al., 2017). These change processes necessary to tackle global problems have been referred to in their entirety as the *great transformation* in the sense of a "worldwide remodeling of economy and society towards sustainability" (WBGU, 2011, p. 5). The sustainable bioeconomy must be regarded as one building block of this great transformation.

Such profound societal change requires each and every individual to reconsider his/her practices and attitudes. This necessarily involves learning. In the context of transformations towards the fundamentally new socio-economic practices envisioned by a sustainable bioeconomy, learning encompasses more than the acquisition of knowledge. According to one of the targets set for reaching the Sustainable Development Goal (SDG) 4 on inclusive and equitable quality education and the promotion of lifelong learning opportunities for all, education shall activate sustainable lifestyles, human rights, non-violence, and global citizenship (UN, 2015). This postulation considers learning as part of an education which " must not just be the communication of purely cognitive knowledge, but must also encompass, on the one hand, practical aspects which can be applied to actions and, on the other hand, competence building to enable those learning to reflect on their actions, and empowering them to shape their future" (de Haan, 2003; WBGU, 2011, p. 354).

The article at hand aims at inspecting academic bioeconomy education for its practical, reflexive, and empowering capacities. More concretely, we analyze to what extent the curricula of European bioeconomy programs consider the conveyance of what we refer to as *transformative knowledge*. Although, as emphasized by the SDG's, it is important to involve society as a whole in the learning process for the envisaged transformation to a bioeconomy, this paper focuses on academic education only. This is motivated by the assumption that academics play a central role as multipliers in processes of systems change in a knowledge society (Adomßent, 2013; Fadeeva et al., 2014; Sipos et al., 2008; Steuer and Marks, 2008). Based on the argument that a transition to a sustainable bioeconomy requires transformative knowledge, the authors pose the following research question:

> Are the curricula of European bioeconomy graduate programs designed in a way that they account for the conveyance of transformative knowledge?

To answer this question, the argument is made that our current global challenges are to be regarded as *wicked problems* whose solution approaches must place an emphasis on knowledge and learning (Section 2). Section 3 spotlights transformative knowledge and explores its role in a comprehensive education dedicated to the bioeconomy. The data and analytical framework for the subsequent empirical study are presented in Section 4. The results of the analysis (Section 5) and their discussion (Section 6) are followed by concluding remarks and an outlook in Section 7.

2. The nature of global challenges and the need for knowledge

The development of innovative technologies that help substitute fossil by bio-based resources, certainly is a sine qua non for a transformation process towards sustainability. However, the nature of the grand challenges humanity is currently confronted with has been found to be of a complex nature and technological substitution processes alone will hardly suffice to confront them (Pyka, 2017b; Schlaile et al., 2017). Global challenges like climate change, food security, and resource depletion have been referred to as wicked problems (Hulme, 2009; Wehrden et al., 2017) in the sense that their causes are emergent and complex, they are immanent in the social structure, their effects are uncertain, and consequently it is extremely difficult to manage them (Rittel and Webber, 1973). Conventional thinking, approaches, and methods of problem solving have proven inappropriate for tackling wicked problems. Such approaches generally feature linear top-down processes that start by analyzing the problem, then design and finally implement a solution (Conklin, 2006). In the case of wickedness, the isolated analysis of the problem itself will be futile since "one cannot first understand, then solve" (Rittel and Webber, 1973, p. 162).

Alternative approaches become necessary that emphasize proactive consideration of the interconnectedness, interrelatedness, and interdependence of elements responsible for the problem (Conklin, 2006; Waddock et al., 2015), as opposed to curing the symptoms without affecting the problematic architecture of the system. Such approaches will need to deviate from linear thinking and instead focus right from the start on the entirety of actors and processes involved (McCormick and Kautto, 2013). It is debatable and indeed currently debated, whether ostensibly technocratic solution approaches such as the bioeconomy offer adequate answers to the type of challenges we are facing (Bugge et al., 2016; Hausknost et al., 2017; Heimann, 2019). Ultimately, the whole system needs to be taken on board to explore, understand, and eventually manipulate the interrelations between causes and effects, mediating between winners and losers, and complementing reactions with actions. Technological bio-innovation must thus be flanked by social innovation and progress must not be defined in techno-economic terms alone (Schlaile et al., 2017).

The resistance of social systems to fundamental behavioral and technical change has been explained by path dependencies of economic, social and political development (Barnes et al., 2004). Very often, existing infrastructures and inherited experiences determine the direction of progress, as well as established, often institutionalized, knowledge (Abson et al., 2017). This knowledge allows for orientation in a complex world, but at the same time includes the risk of sticking to certain traditions for too long and ruling out promising alternatives too early. One prominent example for society's reliance on established knowledge and practices is the so-called *carbon lock-in* (Unruh, 2000): Despite their obvious environmental and (long-term) economic advantages over fossil resources (Stern, 2008), bio-based alternatives are still struggling with the perpetuation of their fossil competitors (Narodoslawsky et al., 2008). In addition to infrastructural, institutional, and economic causes (e.g., Kandaramath Hari et al., 2015), the carbon lock-in is a result of prevailing knowledge and value frameworks legitimizing and guiding public, private, and scientific endeavors to search for new solutions to technical problems. This forms the cornerstone of the underlying *technological paradigm* (Dosi, 1982) or *techno-economic paradigm* (Perez, 1985).

So far, fundamental changes in socio-economic paradigms (or *great surge* as Perez (2003) puts it) have been explained by *technological* revolutions following radical advancements in *technological* knowledge and their first applications (Beniger, 1989; Perez, 2016). Consequently, the heuristics of these (evolutionary) innovation models and policy strategic planning based thereon have generally targeted the creation, diffusion, and exploitation of *technological* knowledge. This obviously also applies to policies related to the bioeconomy. However, the exclusive focus on the accumulation of technological knowledge is insufficient in the face of wicked problems which are not purely technological mysteries waiting to be solved. Instead, we need to expand our concept of knowledge necessary to understand the entirety of the problems' causes. This involves search heuristics for innovation processes incorporating a direction of change negotiated by all stakeholders towards a dedicated – as opposed to random - transformation (Schlaile et al., 2017).

Against the backdrop of this novel demand on the conception of innovation, Pyka (2017a) coined the notion of *dedicated innovation systems* (DIS) that target "radical transformations of existing institutions and routines (…) to overcome the inertia of the oil-based paradigm" (Pyka, 2017a, p. 3). Within DIS, knowledge types other than

technological knowledge come into focus since they are expected to act as both, important catalysts for the development of new technologies and a selection mechanism among these technologies during the emergence of new paradigms (Beniger, 1989). In the context of a transformation to a sustainable bioeconomy, such knowledge must encompass an understanding of biogeochemical cycles and social interaction, a conception of equitable and environmentally friendly bio-based value chains along with skills to implement them, and the awareness that some of the underlying assumptions and perceptions of current processes of production and consumption need to be seriously revised (Urmetzer et al., 2018). Ideally, this results in the emergence of a completely novel set of search heuristics, development instructions, and self-commitment on the part of industry with the aim of improving the supply responses to sustainable and bio-based demand requirements. In other words and with reference to Dosi and Nelson (2010), such knowledge could be the basis for more sustainable and bio-based trajectories.

It is crucial to understand the characteristics and the levers for the creation and diffusion of such knowledge and skills regarding norms and values, but also regarding techniques to induce a system change towards desirable ends (Abson et al., 2017). Three types of knowledge necessary to induce transformative change in the face of wicked problems have been identified: systems knowledge, normative knowledge, and transformative knowledge (Abson et al., 2014; ProClim, 1997; Wehrden et al., 2017). These three cognitive spaces are certainly required for an effective confrontation of the wicked problems addressed by the bioeconomy concept, too[1]:

- Systems knowledge: Actors need to understand the systemic embeddedness of the problem, separate symptoms from causes, and scrutinize the interdependent mechanisms that cause the identified problem. For example, the emergence of unforeseen side-effects of land-use change (referred to as *indirect land-use change*) revealed an impressive lack of systemic understanding of the carbon emission problem. In this case, the effects of the well-intentioned policies to increase plant supply for biofuel actually more than nullified the positive effects of biofuel use (Leemans et al., 1996; Searchinger et al., 2008). Likewise, the various causes of malnutrition around the globe and their interdependencies with issues of conflict, corruption, and education will have to be understood for its sustained and sustainable eradication to become possible (Cohen and Reeves, 1995).
- Normative knowledge: Normative issues must be put up for discussion to enable a debate on visions and objectives of how the world should be. A globally agreed canon of normative knowledge, for instance, has been compiled by the United Nations as the *Sustainable Development Goals* (UN, 2015). Likewise, numerous political strategies and initiatives suggest that the visions and objectives of the bioeconomy are obvious and agreed upon in industrialized countries. The normative bases of the various imaginaries, however, have been found to be utterly diverse (Pfau et al., 2014). Consequently, there is still room for discourse on a common understanding of what a sustainable bioeconomy is and what it is not.
- Transformative knowledge: Based on these two types of knowledge, competences must be acquired to effect a transgression from the status quo to the desired state. This requires a revision of inherited values and assumptions as well as the acquisition of skills to effect the desired societal change (Urmetzer et al., 2018). For example, evolving from a fossil to a bio-based economy, the society needs to get rid of the believe in endless and cheap fossil energy as well as the infinite capacity of our ecosystems to absorb emissions and waste. Only then can societal change be instigated on a deep and long-lasting basis.

But how will these three types of knowledge enter societal systems? Since a direct "indoctrination" of apparently important new worldviews must be rejected for ethical considerations, the key to legitimate transformations of personal values can only be education (O'Brien and Sygna, 2013; Schlitz et al., 2010).

Through the UN Decade of Education for Sustainable Development (2005–2014) (UNESCO, 2006), the global community acknowledges the absolute centrality of education in a transformation towards sustainability. However, it has been criticized that the initiatives kick-started during the decade did not embrace a genuinely transformative approach and did not encourage thorough reflection on the values and thinking that led to today's problems (Huckle and Wals, 2015). Without this cognitive space however, a comprehensive transformative education will remain incomplete. The notions of *sustainability literacy* (Stibbe, 2009) and *transformative literacy* (Schneidewind, 2013) explicitly emphasize what has been introduced above as transformative knowledge. It is argued that sustainability education already has much to offer in imparting knowledge *about* sustainability (i.e., systems and normative knowledge). An education truly aiming at promoting the ability to transform oneself, a community or society as a whole towards more sustainability, however, additionally requires conveyance of the skills, attitudes, and values necessary to put society on a more sustainable track (Singer-Brodowski, 2016a; Stibbe, 2009; WBGU, 2011) (i.e. transformative knowledge) - an educational goal that has been termed by Fadeeva et al. (2014) as *fit for transformation*. This is thought to involve participatory learning to provide students with the opportunity to become active paradigm changers (Disterheft et al., 2016). It must be assumed that this also holds true for education aiming at a bioeconomy transformation (Urmetzer et al., 2018). A deeper understanding of the elements and objectives of transformative knowledge in the context of a transformation to a sustainable bioeconomy is needed in order to assess the requirements for formal curricula to effectively convey it.

3. Transformative knowledge

The (largely interchangeable) terms *transformation knowledge* or *transformative knowledge* (TK) are used throughout the literature in two different senses, depending on the context: In the educational field, TK has been defined as "the facts, concepts, paradigms, themes, and explanations that challenge mainstream academic knowledge and expand and substantially revise established canons, paradigms, theories, explanations, and research methods" (Banks, 1993, p. 7). In the context of sustainability transformations, TK is defined as "knowledge on how to shape and implement the transition from the existing to the target situation" (ProClim, 1997, p. 15). The latter includes the competences required to develop effective policies and to apply strategies such as participation, empowerment, education, and communication (Abson et al., 2014, p. 32; Rauschmayer et al., 2015) in order to collectively achieve societal goals. It is this type of "knowledge for action" that sustainability transformation scholars consider the scientific basis for guiding politics and society to design coherent and integrative strategies that induce the combat against sustainability problems (Grunwald, 2004).

At first glance, the two meanings of transformative knowledge – from the educational science and sustainability science perspective - may seem rather unrelated. However, the first dimension of TK can be considered to constitute the required *personal* prerequisite for the acquisition of the second, more *practical* dimension of TK. In fact, the connection of such different *spheres of transformation* (O'Brien and

[1] With reference to what has been stated above it is important to note that the following enumeration shall not imply a chronological order as the knowledge is usually acquired in an unstructured non-linear process where problem statement and solution strategy design co-evolve during an iterative process Rittel and Webber (1973).

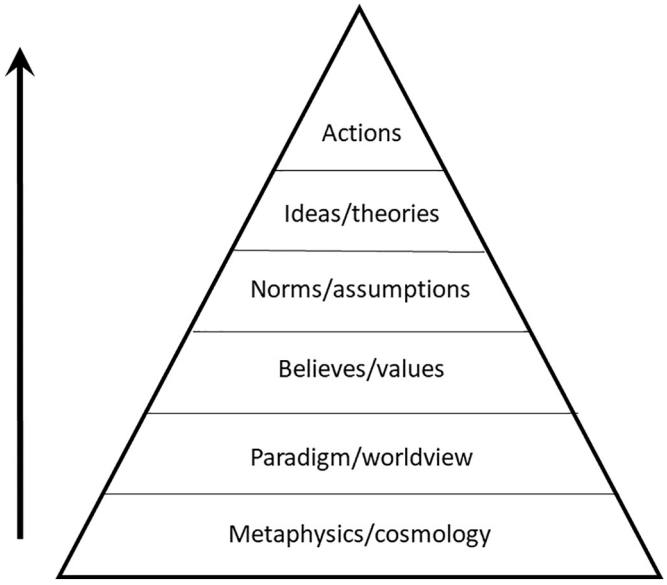

Fig. 1. Levels of knowing adapted from Sterling (2011) based on Bohm (1994).

Sygna, 2013) has been found to be essential for a more comprehensive approach to deliberate transformation towards sustainability, since a regime shift requires a change in "worldviews, institutions, and technologies together as an integrated system" (Beddoe et al., 2009, p. 2484). In other words, "there can be no societal transformation without individual transformation" (Balsiger et al., 2017. P. 358). The relationship between the personal and the practical sphere of TK can be best understood against the background of different levels of knowing (Sterling, 2011) as shown in Fig. 1.

The pyramid illustrates that the ideas and theories that determine our actions emerge as products of our deeper beliefs and values (arrow on the left). To fully understand the characteristics of TK operational towards tackling a certain problem, it is important to acknowledge that the impact of our deeper assumptions on our actions may not be consciously recognized. Only by reaching the different levels of knowing can TK unfold its full potential to enable people to effect behavioral change in themselves, a community or the society as a whole. TK, thus involves the skills to revise deeper levels of knowing and meaning (personal sphere), thereby influencing more immediate and concrete levels of ideas, theories, and action (practical sphere) (Dirkx, 1998; Mezirow, 1991; Sterling, 2011). Translated into the vocabulary of transformation scholars (Abson et al., 2014), a comprehensive canon of TK necessarily involves elements of *motivation* to cover skills on the personal level, as well as elements of *communication and education, participation,* and *policy and decision making* to contribute to the practical transformative abilities of the learner. This terminology helps to operationalize the theoretical deliberations when evidence for TK is sought in bioeconomy curricula in the following section.

While, to date, these elements of TK have been conceptualized exclusively for knowledge relevant for sustainability transitions, they must be considered equally important in the context of a transformation to a sustainable bioeconomy. Elements of the practical sphere of TK in particular can be found among the strategic objectives of several political bioeconomy-related documents. The importance of capabilities for successful *communication and education* with regard to the contents and aims of the bioeconomy is stressed in the European bioeconomy strategy (EC, 2012) and by the German government (Federal Ministry of Education and Research and Federal Ministry for Food and Agriculture, 2015). The closely related element of *participation* is also found to be essential for a successful transformation to a bioeconomy (EC, 2012, 2018; Federal Ministry of Education and Research and Federal Ministry for Food and Agriculture, 2015; Knierim et al., 2018; The European Bioeconomy Stakeholders Panel, 2017). Yet, the required distribution of power over a number of affected parties requires particular *policy and decision making* skills across societal stakeholders which has also been called for by, for instance, the *European Commission* (EC, 2018). Several countries evaluate their bioeconomy strategies and install feedback-cycles to ensure policy learning and improve policy and decision making in the long run (German Bioeconomy Council, 2018).

The TK element relating to the personal sphere, *motivation*, is only touched upon in European bioeconomy publications. However, the German position is hinted at in the statement that for a bioeconomy transformation "successful structural change must take place throughout society" (Federal Ministry of Education and Research and Federal Ministry for Food and Agriculture, 2015, p. 5) and in the call for "comprehensive industrial structural [bioeconomy] transformation toward sustainability" (Federal Ministry of Education and Research and Federal Ministry for Food and Agriculture, 2015, foreword). These phrases can be interpreted as reflecting the will to change paradigms behind production and consumption processes. At the level of the individual, the transformation towards a sustainable bioeconomy is seen to require the personal element of TK, too, by postulating critical involvement "with one's own consumer behaviour" (Federal Ministry of Education and Research and Federal Ministry for Food and Agriculture, 2015, p. 96).

Although a detailed analysis of policy documents would go beyond the scope of this article, the sample of papers screened point to a perceived demand for TK in a transformation towards a sustainable bioeconomy. Following the discussion regarding the nature of wicked problems (Section 2) and the theoretical foundation of TK (this Section), it must be concluded, that TK constitutes a fundamental component of the knowledge base for future decision makers in their contribution to the transformation to a sustainable bioeconomy.

The following empirical Section focuses on the transformative knowledge base of one particular group, namely future academic bioeconomy experts. It was already mentioned that university graduates play an essential role in instigating societal change. As multipliers within societies, e.g. as future politicians, business leaders, and scientists, the academic elites generally play a major role in transformation processes (Adomßent, 2013; Fadeeva et al., 2014; Steuer and Marks, 2008).

Several universities in Europe have recently established programs for the training of such bioeconomy experts (Lask et al., 2018). These international and interdisciplinary programs can be expected to provide profound technical and scientific knowledge based on the high-level academic expertise of the respective institutions. However, it is not clear how well their design accounts for the conveyance of *transformative* knowledge required for future decision makers to contribute to the transformation to a sustainable bioeconomy. For this reason, the compulsory course content as well as the key conceptions of four bioeconomy programs (master's level) were searched for the various elements of TK.

4. Data and methods

4.1. Selection of programs

Our sample of study programs was selected from the European master programs on bioeconomy according to two criteria. In order to ensure comparability, only (1) full-time graduate programs were selected that (2) displayed the interdisciplinary approach to bioeconomy in line with the current European understanding of the topic (EC, 2018). Fulfilment of the second criterion was achieved by those programs that explicitly target the admission of students from diverse academic backgrounds and that explicitly advertise their interdisciplinary training (see Table 1, *Formal admission requirements* and *General aims of the program*). The sampling resulted in the following four programs:

Table 1
Selection of European bioeconomy-related study courses.

Program	M.Sc. Biobased Sciences	M.Sc. in Management of Bioeconomy, Innovation and Governance	M.Sc. Bioeconomy	M.Sc. Wood Materials Science
University	Wageningen University & Research, NED	The University of Edinburgh, GBR	University of Hohenheim, GER	University of Eastern Finland, FIN
Year of establishment	2018	2013	2014	2013
Formal admission requirements	Bachelor's degree or equivalent with a profile in natural sciences, engineering, or quantitatively-orientated social sciences	Bachelor's degree or equivalent with a technological or social sciences profile	Bachelor's degree or equivalent with a technological, economic or social profile	Bachelor's degree or equivalent with a profile in forestry, chemistry, material science, biology, physics, engineering or related field.
Program structure	2-year program	1 – /2-year program	2-year program	2-year program
General aim of the program	The program focuses on the transition from a petrochemical to a biobased society. Graduates are able to assess opportunities/challenges from an interdisciplinary perspective and to design production chains including biomass production, bioconversion, biorefinery and societal, logistic and economic transition processes.	The program responds to the central challenges of the bioeconomy, including: developing sustainable innovation in a responsible manner; identifying and exploiting value throughout innovation ecosystems; and bringing new technologies to existing and emerging markets. Graduates are able to assess how innovation in the life sciences is changing production methods, industrial structures, market dynamics and strategic decision making.	The interdisciplinary program looks at entire bio-based value chains and networks. Graduates are able to examine the ecological, social, and economic dimensions of the bioeconomy on a micro and macro-level. They have the ability to assess the requirements for innovations in the bio-based economy and the corresponding political framework conditions.	The MSc program trains experts who create links between wood and the final products in order to move the forest bioeconomy agenda forward. Graduates understand the entire chain from wood biomass production to product development and innovation management.

(1) Master's Biobased Sciences (Wageningen University & Research, Netherlands; WUR)
(2) Masters in Management of Bioeconomy, Innovation and Governance (The University of Edinburgh, UK; EDI)
(3) Master's Bioeconomy (University of Hohenheim, Germany; HOH)
(4) Master's Degree in Wood Materials Science (University of Eastern Finland, Finland; UEF)

Due to the diversity in academic culture and research profiles, each of the universities has a unique perspective on the bioeconomy and the corresponding graduate programs. Obviously, the nature of the contributing institutes influences the contents of the curricula, which are also constantly evolving due to the plasticity of the bioeconomy as such. Nevertheless, all programs span a number of disciplines and are open to graduates from various backgrounds (e.g., engineering, economics, agricultural and natural sciences). Table 1 presents a brief overview of the selected study programs.

4.2. Methodology

To investigate the extent to which TK elements are conceptually considered in European bioeconomy programs, a hybrid methodology was applied. The approach combined a keyword-based content analysis of the compulsory modules' learning outcomes and semi-structured interviews with key representatives of each program. The use of a hybrid methodology allowed to complement "hard" results codified in the curricula (based on the identification of key-words) with rather "soft" and more tacit elements of the key conception behind the respective programs (obtained from the interviews) (see Fig. 2).

The keywords that guided the content analysis as well as the structuration of the interviews were taken from the compilation derived by Abson et al. (2014). Originally, this list was used to analyze the coverage of the diverse knowledge types relating to sustainability in scientific papers. The keywords are categorized according to the three types of knowledge (systems knowledge, normative knowledge, and transformative knowledge) required to solve wicked problems (Wehrden et al., 2017), i.e. to effect transformative change towards sustainability (Urmetzer et al., 2018). The compilation thus provides a solid fundament for the present analysis of TK imparted in higher education, too. The analytical framework for this study (Table 2) combines the suggested keywords with the theoretical foundations of TK for a transformation towards bioeconomy as deliberated in Section 3. Following Abson et al. (2014) the keywords identified are clustered according to the following four elements of TK:

(1) *Communication & Education*

Given the interdisciplinary nature of the bioeconomy, integrative communication abilities are of major relevance and contribute to the development of skills necessary to involve diverse societal actors - a key issue in any kind of societal transition (Frantzeskaki et al., 2012). This involves the relevant communication skills and competences to inform and involve society (Cörvers et al., 2016).

(2) *Participation*

In order to support and drive a transition towards a sustainable bioeconomy it is essential to (a) acquire the skills to identify and include all relevant stakeholders for a certain project, as well as (b) to handle dispute and dynamics in collaboration processes among these stakeholders. For knowledge-based transition processes such as the bioeconomy, a particular challenge arises where non-academic, societal stakeholders are involved in so-called transdisciplinary research projects (Knierim et al., 2018).

(3) *Policy & Decision making*

The relevance of processes of governance and policy within societal transitions is taken account for by this element. Fundamental knowledge of governance mechanisms and the political framework is necessary for understanding and driving governance processes in transformation processes.

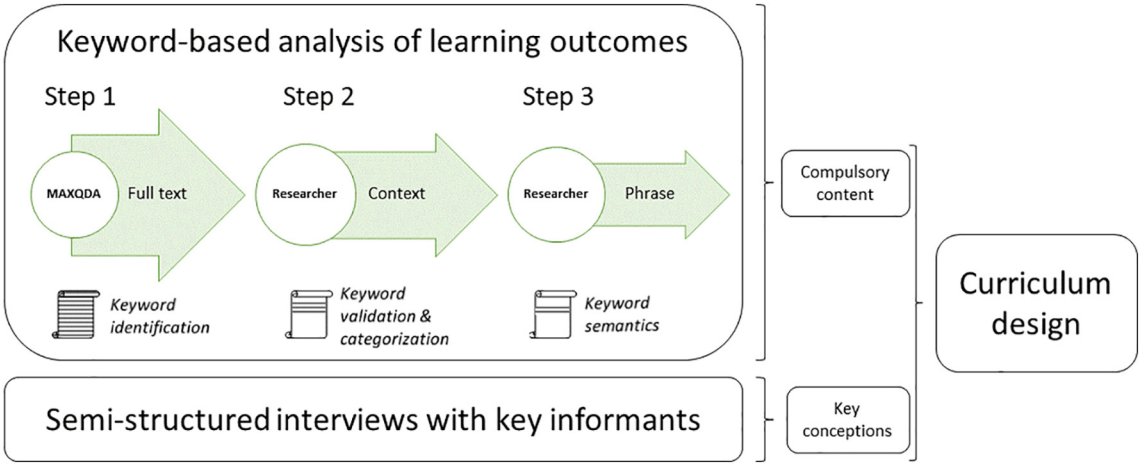

Fig. 2. Overview of the hybrid research approach combining the keyword-based content analysis with the semi-structured interviews.

(4) *Motivation*

As emphasized above, motivational aspects (personal sphere of TK) are indispensable for "comprehensive transformative" knowledge. This necessarily involves the identification and revision of individual assumptions and values (Banks, 1993). In this respect, the keywords identified by Abson et al. (2014) to track down phrases indicating an affiliation with the element motivation cannot be considered exhaustive, as these authors take a rather practical stance on TK. Therefore, further motivational terms were added to the keyword list. These include terms that the authors came across in the course of the analysis which struck them as relevant but were not included in the original keyword list. The reasons are twofold: (1) the broader understanding of TK based on the duality of dimensions (personal and practical); (2) the different foci of the two studies. While Abson et al. (2014) analyzed scientific papers, module descriptions of academic curricula were the research object of the present keyword-based content analysis.

Table 2 illustrates the relation of these four elements (second column) to the two spheres of TK (first column) and substantiates them with relevant skills and competences (third column). The keywords expected to indicate coverage of the respective elements are listed in the fourth column.

4.2.1. Keyword based content analysis of the bioeconomy curricula

International comparability of European qualifications and course contents has been greatly improved in the course of the Bologna Process (Bologna Working Group, 2005). A major achievement of this standardization process is the broad availability of *module descriptions* for courses taught at universities in Europe. These descriptions summarize contents and learning outcomes, including knowledge, skills and competencies, and can thus be considered useful proxies for the analysis of knowledge types aimed for by the programs in question.

As a first approximation to the course contents, the selected study programs were screened for the presence of TK elements by means of a keyword-based content analysis. The unit of analysis was the module descriptions collected from publicly accessible sources (university homepages, module catalogues). Only compulsory modules were looked at, since they represent the fundament of the program in question and can be expected to contain those contents that are considered relevant to be taken up by all graduates.

By means of the program MAXQDA (VERBI Software GmbH, 2018),

Table 2
Analytical framework for the structuration of keywords and interviews.

Transformative knowledge sphere	Elements of transformative knowledge	Relevant skills and competences	Keywords, as suggested by Abson et al., 2014
Practical	• Communication & Education	• Communication skills to inform and involve society (Cörvers et al., 2016)	Communicable, communicate, communicating, communication, communications, communicative, education, educational, learn, learned, learning
	• Participation	• Strategic skills to plan and implement general participatory processes within which credible, shared and feasible strategies are developed (Wiek and Kay, 2015).	Democracy, democratic, empower, empowerment, inclusive, inclusivity, institution, institutional, institutions, participant, participants, participate, participated, participating, participation, participatory, pluralism, pluralistic, practitioners, stakeholder, stakeholders, transdisciplinary, engage, engaged, engagement, *team*[a], *collaborative*[a], *collaborate*[a], *cooperation*[a], *cooperate*[a]
	• Policy & Decision making	• An understanding of the processes and governance mechanisms at work in transformations from the current state (systems knowledge) to the desired state (normative knowledge) of the system (Abson et al., 2014).	Decision, decision(-)makers, decision(-)making, decisions, deliberation, deliberative, enforcing, govern, governance, governed, governing, legislation, legislative, multicriteria, policies, policy, policymaker, policymakers, policymaking, facilitate, facilitated, facilitates, facilitating, facilitation, facilitative
Personal	• Motivation	• Ability to revise individual assumptions and values (Banks, 1993).	Activists, advocacy, aspiration, attitude, attitudes, attitudinal, belief, beliefs, idealism, idealistic, ideals, incentive, incentives, inspiration, leadership, legitimacy, legitimate, motivate, motivated, motivation, motivations, motives, encourage, encourages, transformability, *reflection*[a], *reflect*[a], *reflexive*[a], *reflective*[a]

[a] Added by the authors to the original keyword list of Abson and colleagues.

indicator words within the module descriptions were identified in a first step (see Fig. 2). In a second step, keywords were condensed by validation according to the adjacent context or *phrase*(*s*) as these text segments are referred to in the following. This step lead to a first reduction of the stock of material to be analyzed. Phrases containing one of the listed keywords were attributed to one of the four TK elements according to the analytical framework shown in Table 2. In the third and final step, some of the phrases were assessed to evaluate their concrete semantics and relevance for the corresponding skills and competences leading to a further reduction in number.

4.2.2. In-depth interviews with key representatives

With the aim to back-up the rather technical keyword-based analysis, additionally four in-depth interviews were conducted with key representatives of each program. The interviews followed a predefined selection of questions loosely structured along the different elements of transformative knowledge, as outlined above. This way, the interviewees were guided towards relevant conceptual foundations of the programs, and at the same time they were offered enough room for bringing in new aspects. A qualitative analysis of the responses was performed in order to systematize the data and deduct the consideration of TK elements in the conceptualization of the programs.

5. Results

In total, 190 TK-related keywords were identified in the module descriptions of the master programs analyzed (step 1, Fig. 2) by means of the keyword-based content analysis. This corresponded to 2.36, 2.33, 2.61 and 1.18% of the total number of words in the module descriptions for WUR, EDI, HOH and UEF, respectively. To the authors' knowledge, there is no guideline for the ideal number of words in the assessment of an adequate inclusion of TK. Nevertheless, with view on our research question it is evident that certain aspects of TK are incorporated in the programs. The further analysis in step 2 led to the exclusion of a number of originally positive results. This applied to terms such as *learn* (HOH), *communication* (EDI), *participant* (WUR) used in relatively generic contexts that were assumed not to be related to the TK space. The results from the keyword-based content analysis were complemented with the insights from the in-depth interviews. In the following, the combined results are presented for each of the four TK elements.

5.1. Communication & education

Both the keyword-based search and the interviews revealed the relevance of skills to effectively communicate with diverse audiences in regard of future bioeconomy experts. For the interviewees from WUR, EDI and HOH, one of the major learning goals was the graduates' ability to understand and use a wide range of vocabularies common to the diverse set of bioeconomy-relevant disciplines and stakeholders. This is also in line with the keyword-based search, in which the identified phrases often referred to communication with(in) different audiences and inter- or even transdisciplinary environments. This included “audiences within food production system[s]” (EDI) and “partners from industry” (HOH). Accordingly, students learn to apply “a variety of communication tools” (UEF) and use an “appropriate style and language for different audiences” (EDI). All the curricula imparted different aspects of communication and the relevant communication skills and competences to inform and involve society were covered. However, as elucidated from the interviews, concrete approaches varied substantially. While some relied on “learning-by-doing in a culturally diverse and interdisciplinary environment “(HOH), others have installed supporting facilitators accompanying the compulsory modules (EDI) or process coordinators in dedicated modules (WUR). At UEF, the required skills were regarded more relevant on a PhD level than for master graduates. Therefore, communication skills play a lesser role compared to the other programs.

5.2. Participation

Concerning the two major participation aspects, stakeholder identification and involvement as well as collaboration, the interviewees agreed on the importance of these aspects for bioeconomy education and confirmed their consideration during the conceptualization of the programs.

Dedicated modules (HOH) or the use of leitmotifs throughout fundamental modules (WUR) were established in order to emphasize the systemic nature of the bioeconomy and the importance of stakeholder considerations. This was also reflected by the keyword-based search which identified relevant phrases. For instance, the recognition of “different stakeholder perspectives” (WUR) and their “role […] in the governance of […] innovation” (EDI) processes in the curricula as well as by “concepts such as participation” (HOH) and necessary methods were featured in the WUR, EDI and HOH curricula. Moreover, the HOH curriculum was unique in that it explicitly included transdisciplinary research. The second major aspect of participation, namely collaboration, was present in all analyzed programs. This includes in particular “teamwork practices” and group assignments in “interdisciplinary team [s]” (UHOH), which ideally take place “within complex collaborative environments” (WUR). By that, the curricula aim to ensure that graduates are able to implement participatory processes considering credible strategies based on consensus. All interviewees considered lectures by and projects with external experts from industry or non-governmental organizations helpful for this purpose, as students are exposed to a wide range of roles and perceptions of stakeholders in this way. However, the interviewees stated that the practical implementation and training of such aspects is challenging, as the contact to extra-university partners is difficult to establish and to maintain. For these reasons, these aspects are often only considered on a theoretical level.

5.3. Policy & decision making

A few phrases relating to the TK element *policy & decision making* were identified in the program module descriptions of HOH, WUR and UEF based on the keyword analysis. By contrast, EDI frequently referred to management and government of risk and policies underlying innovation processes. For instance, the EDI descriptions explicitly covered aspects of setting up an innovation policy conducive to the bioeconomy, taking into consideration “its policy and strategic foundations” (EDI). The interviewee pointed out that students are fostered to understand these dynamics in the bioeconomy through case studies and writing policy briefs. HOH and UEF emphasized the role of policies related to the use and management of “scarce resources” (HOH) and the governance of “biomass reserve[s]”. Particularly, in the HOH curriculum policy and decision making aspects referred to the regulatory role of the government in natural resources management. In the WUR curriculum, there was no mention of similar aspects in the compulsory modules, however the “design of […] policy papers” (WUR) was part of the module description. Interviewees from UEF and WUR highlighted regulation as top-down instruments and fundamental enablers. Diverse governance, policy, and decision making issues are conceptually and implicitly covered along the value chain, a common framework shared by the core modules in HOH and WUR, as claimed during the interviews. The role of consumers as drivers of transition was pointed out by interviewees from WUR and EDI, which is reflected only at a general level in the curriculum. According to the interviewees, the unavoidable trade-offs arising from the alignment of the bioeconomy with the requirements of sustainability are considered important politicalissues for decision-making (EDI, UEF, WUR).

5.4. Motivation

The keyword-based search relating to the motivational aspects of TK yielded very diverse phrases, that covered for instance the

understanding of “innovation incentives” (EDI) and their “structures” (WUR) as well as the comprehension of “academic” (WUR) and “social attitudes” (EDI). Based on this selection, the authors followed step 3 of the keyword condensation procedure by interpreting their respective semantics (see Fig. 2). Three of the identified phrases were considered adequate to stimulate reconsideration of individual attitudes. These were found in the WUR and EDI curricula, where the reflection on “incentive structures of stakeholders” (WUR) and the recognition that “innovation processes are shaped by […] social attitudes and perceptions” (EDI) were part of the compulsory modules of the curriculum.

Throughout the interviews, important insights related to the personal experience and transformational stimulation of students were identified in all four programs. For instance, due to the diverse background of lecturers and the different approaches to bioeconomy, students are confronted with a plurality of visions and perspectives (HOH). This partly alleviates the risk for students to assume the perceptions of the individual lecturers as undebatable (UEF). To support students in reflecting on the ideas and knowledge perceived in relation to their own interpretation, EDI has created dedicated spaces to appropriately moderate such processes. In the same vein, UEF and WUR actively encourage students in special modules to question and critically assess statements and exchange ideas in special modules and also try to provide the respective space in other core modules (UEF, WUR). Additional approaches such as de-construction and co-creation contribute to criticize and understand key concepts like sustainability or value (EDI). As a result, students' personal attitude towards the bioeconomy is likely to change during their studies (UEF, EDI). Ethical aspects were highlighted by the interviewee from WUR as principally covered in undergraduate programs rather than at the master's level.

6. Discussion

The literature clearly demonstrates the relevance of TK as a complement to systems and normative knowledge in transition processes (WBGU, 2011; Stibbe, 2009; Singer-Brodowski, 2016a) (see Section 3). While the latter two cognitive spaces form the fundament, TK is required in order to induce a transition from the current to a desired state. The transformation to a sustainable bioeconomy is expected to involve systemic shifts and thus requires the adoption of desired habits, practices, and values in the society. For this reason, bioeconomy-related study programs in higher education need to convey TK. The keyword-based content analysis of curricula of four European bioeconomy graduate programs complemented by in-depth interviews with key representatives of each program yielded valuable insights into this topic.

Before the results are discussed in detail, we want to highlight some of the limitations our research approach displays. Neither the presence of transformation vocabulary in a given curriculum (as derived from our keyword-based analysis) nor its consideration in the conceptualization phase (as derived from the interviews) is a guarantee that it explicitly provides students with comprehensive knowledge on the related concepts. Although it can be assumed that both in combination provide an indication of a general engagement with TK in bioeconomy education, the factual learning outcomes have not been measured. Our results thus only provide evidence for an initial overview of bioeconomy program contents with regard to the inclusion of TK elements. Similar approaches have been applied in previous studies for the assessment of sustainability-related knowledge in scientific publications (e.g., Abson et al., 2014) and in the identification of sustainable development contents in higher education (Singer-Brodowski et al., 2018a).

With these limitations in mind, we are safe to assume that the program curricula assessed hold the potential to contribute to the transformative knowledge base of students. Remarkably, all courses highlight the importance of participatory processes in the bioeconomy transition and emphasize aspects that allow graduates to reach out to a wide range of actors from various disciplines and societal groups. For this purpose, communication across disciplinary and sectoral boundaries is necessary, which partially explains the focus on inter- and transdisciplinary communication approaches in the curricula (esp. WUR, HOH, and UEF). In addition to the interdisciplinary focus of the course contents, the diverse cultural and academic composition of the course participants themselves (found in all the study programs analyzed) is also expected to contribute to the training of the required communication skills.

Considerable variation between the programs is observed with regard to the extent and scope of the element policy & decision making. The strong emphasis on this element in EDI can be attributed to the management orientation of the program and its special focus on the governance of risk. The keywords relating to this TK element are generally used here in the context of economic and innovation policies. In contrast, the curricula of WUR and HOH focus more on public and social policy aspects such as the governance of resources. Against the expectation of several scholars that “the development and impact of the bioeconomy will depend on how it is governed” (Devaney et al., 2017, p. 41, see also Besi and McCormick, 2015; Bosman and Rotmans, 2016), this rather selective consideration of political skills across the programs seems inadequate. A comprehensive integration of all principles of good governance for a future bioeconomy (Devaney et al., 2017) at different levels (e.g., organizations, markets, legislation) is largely missing.

Overall, the keyword-based analysis suggests that only little attention is currently given to the personal sphere of TK (i.e., the element of motivation). At first glance, this may be interpreted simply as an inadequacy, disregard, or reluctance of the analyzed programs to deliberately trigger a change in personal perceptions. Only few module descriptions do involve a reflection on personal or peer attitudes (WUR) and approaches (EDI). This is in line with statements by interviewees who see the development of curricula mainly content-driven. Usually, the program curricula do not offer space for or support reflection. As argued by HOH and WUR, these aspects are rather implicitly included, as students are constantly confronted with diverse and controversial perspectives from their peers or the lecturers. The interdisciplinary and intercultural studentship as well as the diversity of teaching personnel naturally trigger reflection processes on individual perceptions of aspects related to bioeconomy and sustainability. Consequently, the motivational element of TK is incidentally conveyed at a general level, transversally and throughout the whole learning experience in the sense that these are not primarily and purely covered by any specific module.

However, it should be kept in mind that the explicit integration of individual reflection processes may often not be possible to stipulate in formal curricula. It has been shown by education scientists that a change in a student's perspective can only be facilitated, never steered (Singer-Brodowski, 2016b), and the reflection process is expected to be ongoing without ever being completed (Dirkx, 1998). These characteristics render respective learning contents and outcomes impossible to codify. In addition, open-ended learning objectives seem to be at odds with the traditional self-conception of teachers, who aim at fulfilling a syllabus imposed upon them by the university or their respective disciplines.

While the reconsideration of individual assumptions and worldviews may be too personal and its aim too vague to be formally described, let alone measured, educational scientists have given much thought to the conceptualization of the initiation of such reflection processes in adults (Dirkx, 1998; Singer-Brodowski, 2016b). They have framed such perspective change of personal believe systems using the theory of *transformative learning* (Mezirow, 1978, 2000). Transformative learning “refers to transforming a problematic frame of reference to make it more dependable … by generating opinions and interactions that are more justified. We become critically reflective of those beliefs that become problematic.” (Mezirow, 2000, p. 20). According to the model of *progressive change* (Hicks, 2002; Rogers, 1994), the process of transformative learning is one important step towards the development of informed choices for action at personal, social, and political levels. In

other words, transformative learning can be understood as one important step towards attaining TK.

While the scope of the present study does not allow for an analysis of the teaching methods and assessment practices, the authors acknowledge the importance of such components, especially for the development of the personal sphere of TK. Fortunately, educational settings to encourage reflection and critical thinking for a future-oriented academic training are not expected to be overly subject-specific. Programs dedicated to train transformative bioeconomists are thus well advised to draw on experiences documented, for instance, within the context of education for sustainable development (Singer-Brodowski et al., 2018b).

7. Conclusion

In times of unprecedented global challenges that seriously threaten the Earth's capacity to further sustain humanity's existence, society must pursue equally unprecedented future strategies. Since “we can't solve problems by using the same kind of thinking we used when we created them” (quote attributed to Albert Einstein), such strategies fundamentally require a reconsideration of established mindsets to design and follow more sustainable pathways. High expectations currently rest on the idea of superseding the fossil-based by a bio-based economy. It aims at relieving some of the global wicked problems connected with the excessive use of non-renewable resources, including climate change and the irreversible depletion of the Earth's natural resources.

The protagonists of a transformation to a sustainable bioeconomy will be in charge to acquire and apply alternative types of knowledge. Traditionally, economic transformations have been attributed to an accumulation of cutting-edge scientific and technological skills. In the case of sustainability transitions however, additional competences have been identified as relevant. Transformative actors need to understand the interdependent nature of current systems, establish a normative vision of alternative scenarios, and be able to effect a transgression from the current to the desired state. This article has reviewed the latter of these three cognitive spaces: *transformative knowledge*. It involves skills for successful communication and education, the ability to plan and conduct participatory processes, policy and decision-making competences, as well as the capacity to reconsider inherited values and assumptions. All of these elements have been shown to be of utmost importance for a successful transformation to a sustainable bioeconomy by paying tribute to the necessity of “new thinking” for fundamentally new solution strategies.

The analysis of four European graduate programs dedicated to training future bioeconomy experts revealed that they are principally well designed to account for the conveyance of TK. Many aspects of TK are generally well represented in the module descriptions, while other aspects have at least been considered during the conceptualization of the programs. Communication skills and participation approaches in particular form part of all curricula analyzed. Syllabus components identified for the training of policy- and decision-making competences lack a common understanding of bioeconomy governance. Different programs address different governance levels – from enterprise management to global politics, thus neglecting the central role governance must play *at all levels* in normative transitions like the bioeconomy venture. Motivational aspects relating to the reflective capability required to promote change and to overcome structural and social inertia were hardly considered in the module descriptions or during the conceptualization of the programs. Tacitly and unintentionally, however, they have found their way into the curriculum design process, especially in EDI.

Our findings may well serve as a baseline for further development of curricula and pedagogic strategies in bioeconomy education. While we cannot make any qualitative statements on the capacity of the analyzed study programs to educate transformative bioeconomy experts, we do claim that the following aspects should be considered in general when (re-)designing truly transformative bioeconomy programs in the future:

1. The role of governance in the transformation to a sustainable bioeconomy must become clear. Graduated bioeconomists must comprehensively understand the importance of adequate governance at all levels and be trained in shaping political processes.

2. The personal sphere of TK, also referred to as the element of motivation, must be promoted more strongly. The fact that in all four programs deep personal reflection seemed to resonate within the curriculum, shows that there is an awareness of its necessity which deserves more attention in the future. New pedagogical approaches drawing on transformative learning or education for sustainable development could support the education of change makers and experts for a future European bioeconomy, who break unprecedented ground and promote a successful transformation.

Our research is clearly limited by the explanatory power of our analysis. This is, firstly, due to the fact that the set of keywords based on Abson et al. (2014) may be neither exhaustive nor entirely adequate in an educational context. Secondly, the huge discrepancy between the very subjective and personal nature of TK and the rather technical keyword-based approach could only partially be alleviated by the additional in-depth interviews. Future research has to further advance this field of inquiry in at least two directions: the set of keywords should be developed further by employing more sophisticated methods of keyword construction and subsequent content analysis. Also, the conveyance of desired kinds of knowledge (also including systems knowledge and normative knowledge) in study programs could be analyzed in more depth, e.g. by including surveys among graduates and teaching personnel.

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