

Techno-economic and ecological assessment approaches for new biomass value chains

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Abstract:

Utilization of biomass for energetic and material purposes aims to substitute fossil carbon sources to achieve more sustainable value chains. Sustainability analysis and assessment approaches play an important role in the development of these new bio-based supply chains to support the technological development by identifying key figures and providing an objective basis for the discussion and communication of such concepts with stakeholders and political decision makers. This article proposes a framework for analysis and assessment of bio-based value chains at an early process development stage with adaptability for relevant particularities of the considered value chain. The framework is applied for three case studies - the assessment of a lignocellulosic biorefinery concept, an integrated biorefinery concept for several biotechnological and chemical conversions of various domestic oil seeds and an assessment approach for a biochar value chain with thermochemical conversion technologies and biochar application for soil improvement.

Keywords: *Techno-economic assessment; biomass; LCA; biorefinery*

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1. Introduction

A widely discussed approach for the development of more sustainable industrial supply chains is the substitution of fossil carbon sources in energetic and material utilization by renewable, i.e. biogenous, raw materials to reduce environmental impacts, e.g. climate relevant emissions, and abiotic resource depletion, and to reduce the dependency on raw material imports. To achieve these aims there is an abundance of new bio-based supply chains under discussion and development. In these developments, analysis and assessment can assist researchers and decision makers at an early development stage and serve as a basis for the discussion and communication of these concepts with stakeholders and political decision makers. Particularities of respective supply chains have to be considered. For the analysis and assessment the whole supply chain has to be regarded. Bio-based supply chains are composed of five main steps, (i) the raw material production and provision (c.f. e.g. Lorenz et al., 2010; An et al., 2011; Larkum et al., 2012), (ii) technical conversion (e.g. Haase, 2012; Trippe et al., 2011), (iii) product use, (iv) end-of-life and (v) logistical aspects (e.g. Kaltschmitt and Hartmann, 2001; Fröhling et al., 2011). The characterization of new bio-based supply chains has demonstrated that a single analysis and assessment approach to cover all the relevant aspects is not achievable. Therefore we suggest a material and energy flow orientated framework that is explained in the following by an application on case studies for new concepts of bio-based value chains and processes.

2. Material and methods

The framework for economic and ecological assessments of new bio-based processes and value chains is orientated on the structure of life cycle assessment (LCA) methodologies (c.f. DIN, 2009; DIN, 2006). The approach consists of an analysis part with (1) determination of system boundaries, level of detail and basic configuration and (2) modeling of material and energy flows. Step (3) comprises the economic and ecological assessment. An overview is given in Fig. 1. The application of the concept and its case adaptability is exemplary shown in the following sections in three case studies focusing on different supply chain steps - on raw material production, technical conversion concept and product usage (c.f. introduction).

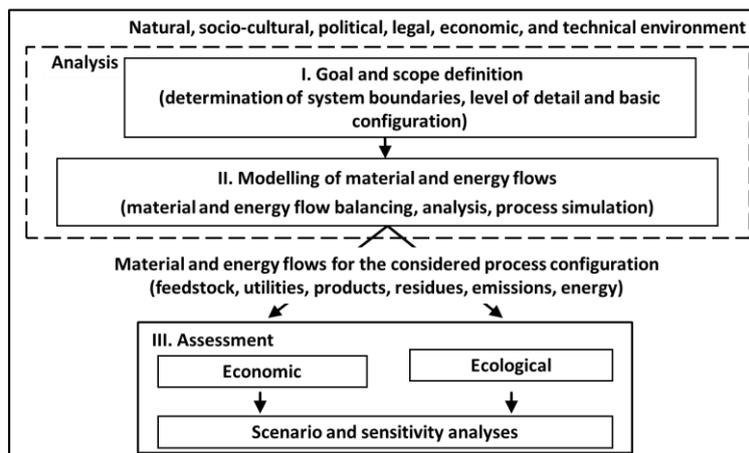


Fig. 1 Overview over the conceptual framework.

3. Results – framework application on case studies

Case study 1 – Integrated biorefinery with new domestic vegetable oils as feedstocks:

Step 1: In the integrated biorefinery concept oils from new domestic oil seeds (different fatty acid composition than conventional vegetable oils) are processed in several conversion steps to various (new) products. For the assessment the value chain is divided in its processing steps with feedstock production, oil extraction, transesterification and new developed conversion steps to new products. An overview over the system boundaries and value chain steps is shown in Fig. 2. The focus lies on the assessment of the feedstock production.

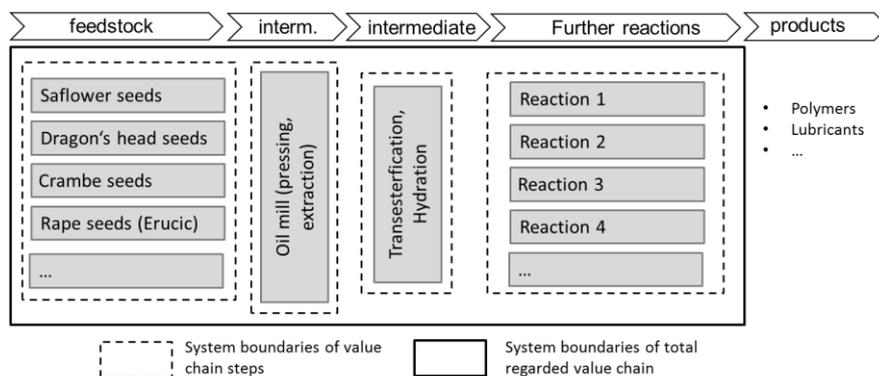


Fig. 2 Overview over integrated biorefinery value chain, system boundaries, feedstocks and processes.

Step 2: The material and energy flows of the agricultural oil seed production (e.g. amount of fertilizer, necessary fieldwork) are based on cultivation data and are adapted for the new oil seeds. The flows of the new processes are based on experimental data from lab scale and up-scaling. All flows for possible process combinations are then modelled in petri-networks with the software Umberto[®] using the ecoinvent database (ecoinvent, 2010) for Life Cycle Impact Assessment (LCIA).

Step 3: In the economic assessment production costs for each step of the value chain are calculated and summarized in product production costs and possible market prices. In the ecological assessment midpoint impact categories are considered and compared with reference systems e.g. oil seeds with conventional rape seeds. Sensitivity analyses indicate a high dependency on oil (seed) prizes because of relatively low seed yields. But specific fatty acid composition may provide technical advantages for products.

Case study 2 – Lignocellulosic biorefinery:

Step 1: The lignocellulosic biorefinery aims to maximize the material usage of national wood resources. As suitable feedstock beech wood residues were identified which are converted to platform chemicals (glucose, lignin, C5-sugars) via an organosolv pulping process and enzymatic hydrolysis. The processes were developed during a research project and different process configurations are considered. The system boundaries for the assessment include forestry production, chipping and transport of beech wood chips and the biorefinery process (cradle-to-gate analysis). The focus of the assessment lies on the biorefinery process to identify key parameters for a possible realization at industrial scale at an early development stage.

Step 2: The material and energy flows are based on experimental data from lab scale which are up-scaled. The flows of the biorefinery process itself are modelled and simulated in ASPEN PLUS[®] for a capacity of 400,000 t dry wood per year and an operation of 8000 h/a. The resulting material and energy flows of the plant and the other flows of the regarded value chain are modelled afterwards in Umberto[®] and the ecoinvent database.

Step 3: In the economic assessment the investments of the biorefinery plant at industrial scale are estimated as well as the production cost for the products. The estimated production costs for glucose lie between 218 and 257 €/t glucose and are 55-66% lower than sugar market prices. In the ecological assessment the environmental impact categories climate change, acidification, eutrophication, land use (competition) and the fossil cumulative energy demand (CED) are considered. In all categories a reduction of 50-80% compared to reference systems occur except for land use (competition) because of wood as feedstock. The assessments show a potential competitiveness, benefits and feasibility of the biorefinery value chain. Further information and results in: Michels, 2009; Haase, 2012; Michels, 2014; Laure and Leschinsky, 2014.

Case study 3 – Assessment of biochar value chain with biochar as soil amendment in agriculture:

Step 1: Biochar has shown in pot and field experiments to serve as a carbon sink over hundreds to thousands of years, to increase biomass yields and to reduce soil greenhouse gas emissions, e.g. N₂O. But results are not ensured and mechanism research is ongoing. To assess whether biochar application is economically and ecologically benefiting the value chain from the biochar production via pyrolysis or hydrothermal carbonization, transportation and biochar application in agricultural soils for soil improvement is regarded. The assessment focus lies on the usage of the product as soil amendment.

Step 2: For material and energy flows of biochar production, transportation and agricultural production literature data are used and adapted. For different soils and climate conditions, literature data of biochar impacts are rare and studies are expensive and take a long time. Therefore for a first assessment, the biochar impacts on soil and biomass production are simulated by the usage of an ecosystem model.

Step 3: In the economic assessment biochar prizes, biomass yields and biomass production costs are estimated and the net present values are calculated. In the ecological assessment the focus lies on CO₂-equivalent balancing. Furthermore external costs and benefits for CO₂-equivalent sequestration are considered. Assessment method, research and results are part of an ongoing PhD-Thesis (Laure, unpublished).

4. Conclusion

The economic and ecological assessment of three case studies showed that the stepwise approach of the framework – with problem definition, material and energy flow balancing and economic and

ecological assessment – is an appropriate tool to analyze and to assess new bio-based value chains with various particularities. The three case studies with focus on different supply chain steps (feedstock to product use) demonstrated that the approach is adaptable for numerous problems because an adequate method selection for material and energy flow calculation (e.g. flowsheeting, ecosystem modelling) and for economic and ecological assessment (e.g. investment estimation, production cost estimation, NPV, LCA, carbon balancing and others) is an integral part of the concept and allows a general transferability of the framework along with an individual analysis and assessment approach for each case.

5. References

- An, H., Wilhelm, W.E., and Searcy, S.W. 2011. Biofuel and petroleum-based fuel supply chain research: A literature review. *Biomass and Bioenergy* 35(9): 3763-3774.
- Deutsches Institut für Normung e.V. (DIN) 2006. DIN EN ISO 14044: Umweltmanagement - Ökobilanz - Anforderungen und Anleitungen. Berlin: Beuth.
- Deutsches Institut für Normung e.V. (DIN) 2009. DIN EN ISO 14040: Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen. Berlin: Beuth.
- ecoinvent Centre 2010. ecoinvent data v2.2., ecoinvent reports No 1-25, Swiss Centre for Life Cycle Inventories, Dübendorf.
- Fröhling, M., Schweinle, J., Meyer, J.C., and Schultmann, F. 2011. Logistics of Renewable Raw Materials: In: R. Ulber, D. Sell and T. Hirth: *Renewable Raw Materials - New Feedstocks for the Chemical Industry* (pp. 49-94). Weinheim: Wiley.
- Haase, M. 2012. Entwicklung eines Energie- und Stoffstrommodells zur ökonomischen und ökologischen Bewertung der Herstellung chemischer Grundstoffe aus Lignocellulose. Karlsruhe: KIT Scientific Publishing.
- Kaltschmitt, M. and Hartmann, H. 2001. *Energie aus Biomasse*. Berlin: Springer.
- Larkum, A.W.D., Ross, I.L., Kruse, O., and Hankamer, B. 2012. Selection, breeding and engineering of microalgae for bioenergy and biofuel production. *Trends in Biotechnology* 30(4): 198-204.
- Laure, S. unpublished. Ökonomische und ökologische Bewertung der Anwendung von Biokohle zur Bodenverbesserung in der Landwirtschaft. Ph.D. dissertation, KIT.
- Laure, S. and Leschinsky, M. 2014. Assessment of an Organosolv lignocellulose biorefinery concept based on a material flow analysis of a pilot plant. *Proceedings of the 5th Nordic Wood Biorefinery Conference*. Stockholm.
- Lorenz, A.J., Gustafson, T.J., Coors, J.G., and de Leon, N. 2010. Breeding maize for a bioeconomy: A literature survey examining harvest index and stover yield and their relationship to grain yield. *Crop Science* 50(1): 1-12.
- Michels, J. 2009. Pilotprojekt, "Lignocellulose-Bioraffinerie" gemeinsamer Schlussbericht zu den wissenschaftlich-technischen Ergebnissen aller Teilvorhaben. DECHEMA Gesellschaft für Chemische Technik und Biotechnologie, Frankfurt [and others] Hannover, Technische Informationsbibliothek u. Universitätsbibliothek.
- Michels, J. 2014. "Lignocellulose-Bioraffinerie" Aufschluss lignocellulosehaltiger Rohstoffe und vollständige stoffliche Nutzung der Komponenten (Phase 2). DECHEMA Gesellschaft für Chemische Technik und Biotechnologie, Frankfurt [and others] Hannover, Technische Informationsbibliothek u. Universitätsbibliothek.
- Trippe, F., Fröhling, M., Schultmann, F., Stahl, R., and Henrich, E. 2011. Techno-economic assessment of gasification as a process step within biomass-to-liquid (BtL) fuel and chemicals production. *Fuel Processing Technology* 92(11): 2169-2184.