Final report

1. Project details

Project title	Sustainability Assessment of Integrated Energy Technologies (SustEnergy)
File no.	64017-0044
Name of the funding scheme	EUDP
Project managing company / institution	Danmarks Tekniske Universitet, DTU Miljø
CVR number (central business register)	30 06 09 46
Project partners	DTU Chemical Engineering, DTU Compute, Ørsted, Lemvig Biogas
Submission date	08 February 2021

2. Summary

2.1 English summary

The goal of SustEnergy is to develop a process-oriented life cycle assessment (LCA) model targeting integrated energy technologies. The aim is to provide a consistent platform for quantitative sustainability assessment of energy technologies and energy systems, and to enable technology owners to prioritise their development efforts according to the environmental importance of individual unit-processes and process parameters of the technology. For assessment of integrated technologies such as biorefineries and power-to-X concepts with several interlinked processes and mutual dependencies, a process-oriented focus is needed to appropriately represent the transitions and transformations of the physical flows (energy, material, substances) with the system. The project involved the following specific objectives: 1) Establish process-oriented life-cycle inventories for integrated energy technologies, with focus on power-to-gas concepts as an illustrative case. 2) Further develop the existing EASETECH model to facilitate process-oriented LCA modelling. 3) Establish relevant LCA sub-models in EASETECH and thereby provide "building blocks" for process-oriented modelling of integrated energy technologies. 4) Perform relevant case-studies addressing selected power-to-gas concepts. 5) Disseminate and communicate modelling principles, datasets and demonstrate use of the modelling tool. Based on the project, EASETECH has been extended with a new "editor" (EASETECH+) allowing creation of new process modules in EASETECH. Based on a range of thermal and biological technologies for gas production as well as regional case-study scenarios, these modules have been used for process-oriented LCA modelling in EASETECH. The model and project results have been disseminated via conference presentations, seminars, webinars and used in university teaching of bachelor to PhD level students.

2.2 Danish summary

Målet med SustEnergy er at udvikle en proces-orienteret model til livscyklusvurdering (LCA) af integrerede og multi-output energiteknologier. Hensigten er at tilvejebringe en konsistent platform for kvantitativ bæredygtighedsvurdering af energiteknologier og energisystemer, og muliggøre prioritering af teknologiudviklingen mod de miljømæssigt mest betydende dele af en teknologi. Livscyklusvurdering af energiteknologier, som for eksempel bioraffinaderier og power-to-X koncepter med mange forbundne og afhængige processer, kræver en proces-orienteret tilgang for på rette vis at kunne repræsentere ændringer af de fysiske strømme (energi, materiale, stoffer) gennem systemet. Projektet omfattede følgende specifikke formål: 1) Etablering af proces-orienterede teknologidata, med fokus på power-to-gas koncepter som illustrativt eksempel. 2) Videreudvikling af den eksisterende LCA model EASETECH til at muliggøre proces-orienteret LCA modellering. 3) Etablering af del-modeller i EASETECH i form af "byggeklodser" som understøtter proces-orientered modellering i EASETECH. 4) Gennemfør relevante cases med udgangspunkt i udvalgte power-to-gas koncepter. 5) Demonstration af modelanvendelsen og formidling af projektets resultater, modelleringsprincipper, og data. Baseret på projektet er EASETECH blevet udvidet med en ny "editor" (EASETECH+), som muliggør etablering af nye procesmoduler i EASETECH. Ud fra en række cases med gasproduktion baseret termiske og biologiske processer er anvendelse af disse moduler demonstreret i udvalgte scenarier på systemniveau. Modellen og projektets resultater er blevet formidlet via præsentationer på konferencer, seminarer, webinarer og anvendt i undervisningen af studerende fra bachelor til PhD niveau på DTU.

3. Project objectives

The overall aim of the SustEnergy project was to develop a dedicated life cycle assessment (LCA) model targeting assessment of integrated energy technologies. The goal was to provide a consistent platform for quantification of the sustainability of energy technologies and energy systems, and to enable technology owners to prioritise their development efforts according to environmental benefits. The LCA model was developed as an extension of the modelling tool EASETECH which has a wide user base within residual resource management. The outcome of the project was a modelling tool that facilitates process-oriented LCA modelling of energy technologies and offers end-users with a library of ready-to-use LCA sub-models (i.e. life-cycle inventory datasets plus models of relevant unit processes comprising key biological and thermal energy technologies).

The project had the following specific objectives: 1) Establish process-oriented life-cycle inventories for integrated energy technologies, with focus on power-to-gas concepts as an illustrative case. 2) Further develop the existing EASETECH model to facilitate process-oriented LCA modelling. 3) Establish relevant LCA sub-models in EASETECH and thereby provide "building blocks" for process-oriented modelling of integrated energy technologies. 4) Perform relevant case-studies addressing selected power-to-gas concepts. 5) Disseminate and communicate modelling principles, datasets and demonstrate use of the modelling tool.

4. Project implementation

Overall, the project has completed the intended activities and fulfilled the project goal. As the project has focused on model development, two aspects have been important with respect to implementation: a) model software programming and b) availability of energy technology data for implementation of case-studies.

The project involved development of a novel "editor", EASETECH+, that enables end-users to create unit-processes associated with the energy technologies of choice and subsequent import these as "modules" into the LCA modelling tool EASETECH (www.easetech.dk). EASETECH allows life cycle assessment and life cycle cost modelling of both (energy) technologies and systems of technologies. This means that the sustainability of a specific energy technology can be assessed quantitatively in an environmental and socio-economic perspective, e.g.:

- Performance of the energy technology relative to a baseline, e.g. a specific year
- Environmental, climate and economic benefits by alternative scenarios for system integration
- Environmental, climate and economic improvements from introducing a new energy technology in the system relative to the alternative
- Environmental and climate importance of individual unit-processes or process steps within an energy technology, e.g. biomass pretreatment prior to gasification
- Importance of individual process parameters for the overall sustainability of the energy technology

The editor, EASETECH+, allows users to create process modules with very advanced modelling of physical flows (energy, materials, substances) and include process parameters affecting these flows within process and technologies. Importing these modules into EASETECH allows users to carry out LCA modelling of energy technologies at a completely new level, also involving the advanced uncertainty assessment included in EASETECH.

The focus on model development made software programming a critical part of the project. While some challenges were anticipated, the overall testing, validation and implementation of the process-oriented LCA principles required more resources and time than originally allocated. This meant that the software implementation process was prolonged and application of the tool on case-studies likewise was somewhat reduced. Throughout the project period, the project experienced some changes in manning across the project partners. This meant some changes in the time-wise placement of individual activities, in particular with respect to case-studies, and in some cases slightly prolonging of activities. This affected the choice of case-studies and required selection of cases and technologies with the necessary data available, in order to ensure demonstration of the model. As such, priority was placed on model demonstration and validation, rather than wide coverage of relevant energy technologies. This meant less focus on power-to-gas technologies, but on the other hand more focus on development of process-oriented modelling features relevant for integrated technologies such as power-to-X concepts. In particular, for system level application of the model on a full energy system, a regional case in France was selected in collaboration with the Joint Research Centre (Eu Commission) and University of Toulouse.

In the last part of the project, the COVID-19 situation somewhat affected completion of the project, in particular with respect to dissemination through conferences. Overall, however, the project has completed the intended activities and reach the intended goals.

5. Project results

5.1 Overview

The key results from the project can be summarised as follows:

- Establishment of assessment framework for process-oriented LCA modelling
- Implementation of process-oriented modelling in EASETECH based on the extension, EASETECH+

- Demonstration of process-oriented LCA modelling on selected integrated and multi-output energy technologies, including establishment of associated life cycle inventory data
- Application of process-oriented LCA modelling on a full, regional energy system case-study

The above results are outlined in the following sections.

5.2 Process-oriented LCA modelling framework

Reported in Lodato, Tonini, Damgaard, Astrup (2020): A process-oriented life-cycle assessment (LCA) model for environmental and resources-related technologies (EASETECH). The International Journal of Life cycle Assessment.

A new assessment framework focusing on process-oriented LCA modelling was provided.

Within life-cycle assessment, environmental technologies are often modelled as "black-box processes", where inputs and outputs are typically not linked through physical and/or (bio) chemical relationships. This limits the flexibility and reproducibility of models, in particular for energy technologies involving conversion of resources such as biological and thermal gasification systems. Here the conversion of materials and chemical substances in the materials are essential for the environmental performance. An advanced "process-oriented" modelling framework allowing quantitative and parameterised physical-chemical relationships between input material composition and subsequent output products was developed based on the project.

A range of new mathematical operators were provided to enable modelling of processes governing mass/energy/substance transitions and transformations within energy technologies (i.e. relationships between inputs and outputs) through the use of parameters. In contrast to earlier models, relationships now included non-linear responses to changes in parameters. The model facilitates "tracking" of the feedstock material properties from the input to the final products, by establishing mass, substance and energy balances for each conversion unit process. In addition, the process-oriented modelling framework appropriately represented material/substance transition and transformations that were validated by separate calculations and external data.

The assessment framework and principles for process-oriented LCA modelling were demonstrated on a case-study involving biorefinery for production of liquid, solid and gaseous energy products. Two perspectives were evaluated with the case-study: a) the importance of unit-processes and choice of process parameters for the overall sustainability results, and b) the importance of feedstock characteristics for the performance of individual unit-processes.

The below Figure 1 illustrates, schematically, the connection between technology modelling in EASETECH and the more detailed process-models in EASETECH+. LCA modelling in EASETECH (top, left) involves combining a number of individual "modules" representing steps in the process chain. With EASETECH+ (top, right), each of these modules can now be "opened up" enabling detailed modelling of relationships between physical flows and process parameters. An example of this more detailed process-oriented modelling is a biorefinery technology (bottom, left) involving several unit-processes (material generation, pretreatment, hydrolysis, fermentation, and recovery. On this basis, with the combination of EASETECH+ and EASETECH, LCA modelling of integrated energy technologies at a much more detailed level is now possible. For the biorefinery example, this means that the specific performance of the hydrolysis process can now evaluated with respect to the overall environmental performance of the full biorefinery, but also be compared with the environmental importance e.g. of the pretreatment process. This provides better insight into the environmental performance of the technology, and thereby an improved basis for improving the technology.

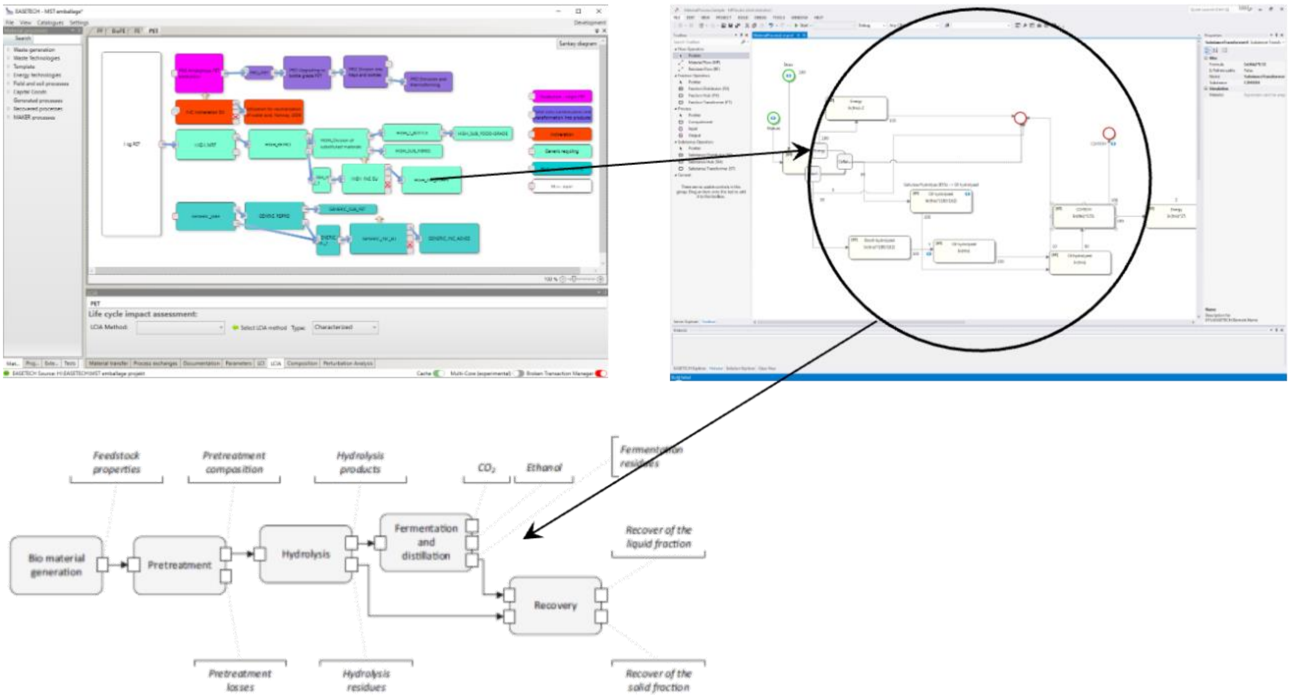

Figure 1. Schematic illustration of the link between EASETECH (top, left) and the editor EASETECH+ (top, right) for a biorefinery case. Please note that the screenshots above are for illustrative purposes only. Partly from Lodato et al. (2020).

5.3 Implementation of process-oriented modelling in EASETECH

Reported in Lodato, Zarrin, Damgaard, Baumeister, Astrup (2021): Process-oriented life cycle assessment modelling in EASETECH. Waste Management.

The existing LCA model, EASETECH, was expanded with a separate editor, EASETECH+, allowing implementation of process-oriented modelling features in EASETECH.

As previously indicated, integrated energy technologies often involves conversion of resources, such as biomass feedstock, into new materials, energy, and byproducts. In these processes, materials or other physical flows (e.g. energy) may often be recirculated or utilised within the same process or in different interconnected processes, and undergo physico-chemical transformations. This implies that physical flows need to be redefined in the modelling. In addition, physical flows can have non-linear responses to changes in model parameters. Background processes, where activities such as extraction of materials can have important impacts on emissions, may also influence the physical flows and thus the environmental performance of the technology. This is often neglected within LCA.

Integration of multiple “if” functions and conditional modelling sequences, is important when comparing physical flows and for implementation of specific operational conditions within an energy technology. These conditions may enable or disable specific physical flows based on data availability, feedstock material properties, and operational process parameters. To support this, EASETECH+ offers the ability to define new material, substance and energy flows and transformations within process, which in turn allow definition of new energy technologies within LCA models in EASETECH. This allow users to evaluate the importance of physical flows, including material recirculation, from background processes to environmental results and the link with other technology types.

The editor was demonstrated on a case-study involving anaerobic digestion of organic waste with production of biogas under different conditions, by importing process-oriented modules from EASETECH+ into EASETECH for LCA of the technology scenario.

5.4 Demonstration of process-oriented LCA modelling on selected technologies

Reported in:

- *Albizzati, Tonini, Chammard, Astrup (2019): Valorisation of surplus food in the French retail sector: Environmental and economic impacts. Waste Management.*
- *Albizzati, Tonini, Astrup (2021): High-value products from food waste: An environmental and socio-economic assessment. Science of the Total Environment.*
- *Ardolino, Lodato, Astrup, Arena (2018): Energy recovery from plastic and biomass waste by means of fluidized bed gasification: A life cycle inventory model. Energy.*
- *Lodato, Tonini, Damgaard, Astrup (2020): A process-oriented life-cycle assessment (LCA) model for environmental and resources-related technologies (EASETECH). The International Journal of Life cycle Assessment.*
- *Lodato, Hamelin, Tonini, Astrup (2021): Framework for assessing environmental performance of methane gas supply in the context of local bioeconomy. Manuscript.*
- *Lodato, Zarrin, Damgaard, Baumeister, Astrup (2021): Process-oriented life cycle assessment modelling in EASETECH. Waste Management.*

The process-oriented modelling principles was evaluated with respect to a range of technology options, with focus on multi-output technologies converting biomass feedstock into a variety of products including energy products. From an environmental assessment perspective, these technologies are complex as the performance of the technology depends on the properties of the feedstock in combination with the process parameters. Conversion of biomass feedstock into energy products, whether liquid, gaseous, or directly electricity/heat, involves a) bio-chemical transformation of the feedstock, b) transitions of the physical flows of materials, energy, and substances within the process(es), and c) relationships with process parameters.

Appropriate LCA modelling of such processes and technologies require that these transformations, transitions and relationships are implemented in the LCA model. The process-oriented modelling framework enables this in a consistent way. Without this the LCA model represents a “black-box” providing little insight into the importance of these aspects for the environmental performance.

Within the project, the process-oriented modelling principles were demonstrated on the following individual technologies:

- Gasification of biomass and plastic waste
- Feedstock pretreatment
- Biogas production from organic waste
- Biorefinery based on a variety of feedstocks

As an example for a biorefinery, the below Figure 2 illustrates the effects of efficiency changes within a single unit-process (the hydrolysis step) for the climate performance of the full biorefinery. The results clearly demonstrate that a single unit-process of an integrated technology, such as a biorefinery, can have profound influence of the overall environmental performance of the technology. This illustrate that environmental evaluations of energy technologies cannot be made based on simplified assumptions about the process and simplified LCA modelling as often provided in literature. In extension of this, Figure 2 also illustrates that the environmental performance is directly affected by the biochemical properties of the feedstock material. While these aspects have been fully acknowledge within biorefinery research, so far this has not been reflected by the LCA models available for environmental assessment of the energy technologies. With this project, EASETECH now enables process-oriented LCA modelling of such technologies.

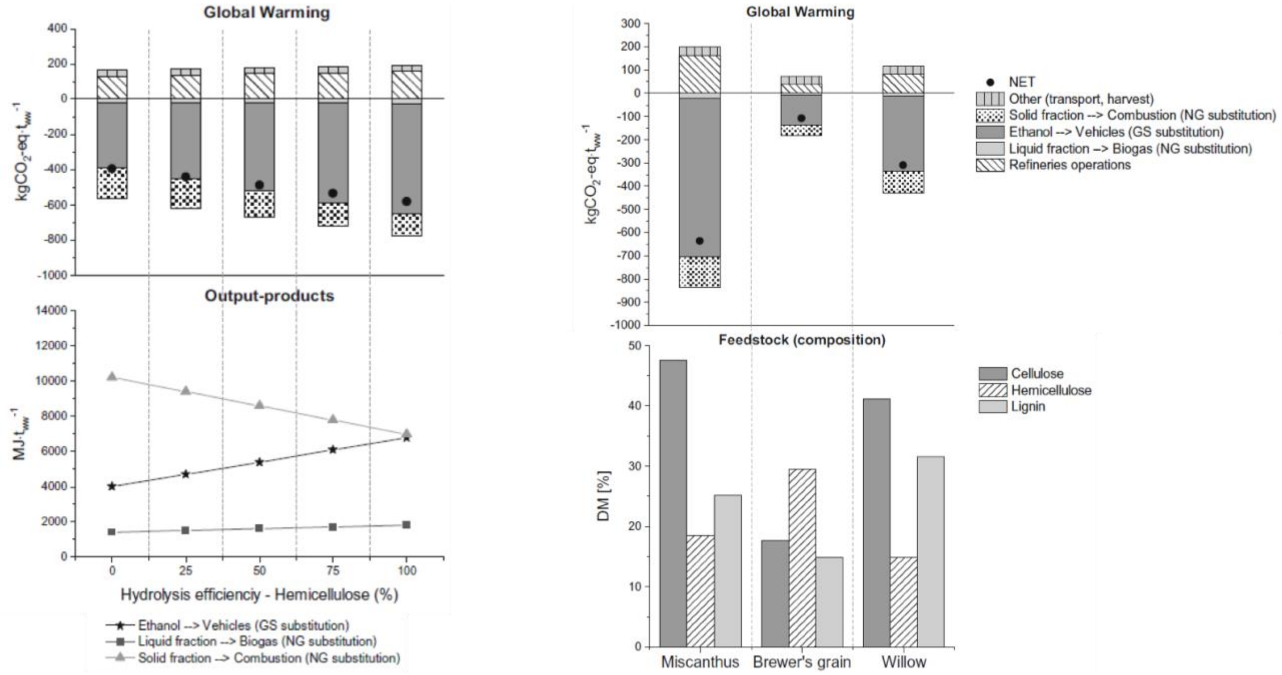

Figure 2. At left, illustration of the importance of hydrolysis efficiency (bottom) for the overall climate performance of a biorefinery (top). At right, illustration of the importance of bio-chemical composition of feedstock biomass (bottom) for the overall climate performance of the biorefinery (top). From Lodato et al. (2020).

Based on the case-studies and model implementation: a) the process-oriented modelling principles has been tested and validated, b) the importance of the bio-chemical composition of the input feedstock has been demonstrated, and c) non-linear parameter relationships and constraints applied based on available technology data. Further, life cycle inventory data for the addressed energy technologies have been collected, organised and utilised in the case-studies.

5.5 Application of process-oriented LCA modelling on regional energy systems

Reported in Lodato, Hamelin, Tonini, Astrup (2021): Framework for assessing environmental performance of methane gas supply in the context of local bioeconomy. Manuscript.

At system level, the process-oriented LCA modelling enables evaluation of individual technologies relative to the entire system, e.g. with respect to process-configurations, system integration, alternative utilisation of feedstock resources (i.e. counterfactuals, CF), and potentials for fulfilling demands for various energy products in the system. Here, the system level assessment is understood as an extension of the previously described modelling of individual technologies.

As an example of methane provision based on anaerobic digestion with hydrogen upgrading of biogas (ADH) and gasification with syngas upgrading (GA) in a French regional context, the below Figure 3 illustrates results from process-oriented LCA modelling. Results are provided for a range of different biomass and biowaste feedstocks (e.g. forest residues, sludge, biowaste, crop residues) all with different counterfactual management of the biomass (i.e. the management of the biomass when not used for energy purposes). The results demonstrate that the climate performance of these two technologies considerably depends on the type of feedstock. While all of the feedstocks offer benefits over the fossil reference (natural gas), then the net results (net balance) demonstrate significant differences between feedstocks. This clearly illustrates that in order to provide relevant environmental performance evaluations of energy technologies and energy systems, aspects such as feedstock properties, counterfactuals, process configuration, and system integration are critical and should be reflected appropriately by the LCA modelling. Based on the project, the LCA model EASETECH now offers the necessary features for this.

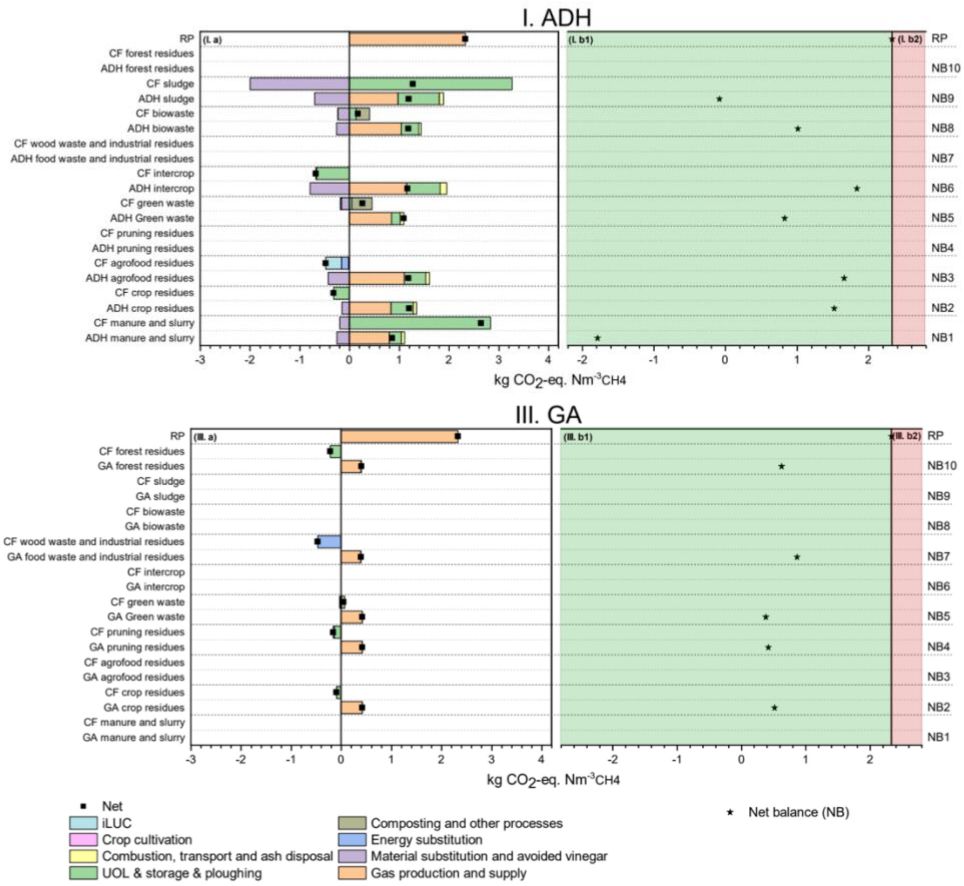

Figure 3. Preliminary results at system level for Global warming (GW) for two technology pathways: a) anaerobic digestion with hydrogen upgrading (ADH, top) and b) gasification with C-to-CH4 upgrading (GA, bottom). On the left, contribution to climate performance from individual parts of the technology system. On the right, net balance (NB) results for each scenario in comparison with the reference product (RP): red areas illustrate scenarios with worse performance than natural gas, while green areas indicate scenarios with better performance. (iLUC = indirect land use change; UOL = use on land). From Lodato et al. (2021), preliminary results.

Based on the case-study involving a French regional energy system (Occitania, southern France), the process-oriented LCA modelling principles were demonstrated and evaluated in at system level. For the case-study a wide range of energy technology and feedstock data were collected, organised and included in the modelling.

6. Utilisation of project results

The project and model development enabled direct collaboration with the Joint Research Centre (JRC) of the EU Commission. While not originally anticipated, this offered a unique opportunity for developing the process-oriented modelling framework with the perspective of subsequent EU-wide application. Collaboration with University of Toulouse further strengthened this basis and allowed direct utilisation of project results for evaluation of the energy system in Occitania with emphasis on the use of local biomass resources for supply of methane gas. Thereby, the case-studies provided specific input to regional energy policy making.

Through the project collaboration, the project partners have significantly improved the modelling infrastructure for process-oriented LCA modelling of energy technologies. The project has provided a tested and validated modelling framework and offered a range of specific modules in EASETECH for use in full-scale projects.

The EASETECH model is hosted by DTU Environment. New users are offered access to the LCA model based on regular training courses. The model tool databases are continuously updated based on new research. As such, new modelling features like those developed in this project are regularly implemented in the model and made available to existing users.

The project has partly supported education of two PhDs in relation to LCA model development and application. EASETECH is used for teaching master level courses at DTU, and is offered as part of PhD courses. Further, the model is used regularly in both bachelor and master theses. Additionally, the project results have been disseminated through conference presentations, workshops, seminars and webinars.

Overall, the project and project results represent an important platform for future research within sustainability assessment of energy technologies, as well as provides an essential basis for industry to evaluate environmental performance of individual technologies and direct development efforts towards environmentally critical parts of the involved processes.

The project outcomes are internationally unique and a similar LCA modelling tool has not been provided previously. With the expansion and developments provided by this project, the EASETECH LCA model tool can now be applied on a wide range of energy technologies and energy systems.

7. Project conclusion and perspective

The project has developed a completely new framework for life cycle assessment of energy technologies focusing on a process-oriented evaluation of technologies. This enables break-down of integrated and multi-output energy technologies, such as biorefineries and power-to-X concepts, into unit-processes and environmental assessment of operational parameters characterising these unit-processes. This provides an unprecedented platform for sustainability assessment of future energy technologies as well as for prioritising technology development efforts towards unit-processes and operations that have significant influence of the overall sustainability. This offers an opportunity for quantitatively substantiating the sustainability claims often associated with new energy solutions.

Concretely, the project has provided:

- Life cycle inventory data for a range of integrated energy technologies for use in process-oriented LCA modelling

- An extension of the LCA model, EASETECH, facilitating process-oriented LCA modelling by creation of new “modules” in the EASETECH+ editor
- Establishment of a range of technology process “modules” in EASETECH that can be used for process-oriented LCA modelling of integrated energy technologies
- Demonstration of the assessment framework and modelling principles by applying the model on a range of individual energy technologies as well as full, regional systems
- Dissemination of the project results to students, PhDs, and industry via courses, seminars, webinars, and industry training courses.

Going forward, the EASETECH/EASETECH+ model framework forms an important platform for quantitative sustainability assessment at DTU. In continuation of previous activities, the model will be applied to a wide range of technology areas, including energy technologies. With the current focus on power-to-X technologies, this area will have particular focus. The aim is that the model can support a wide range of development activities through research at DTU.