Digitization of the work environment for sustainable production

How could algae based sink technologies enable a neutral Product Carbon Footprint?

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1. Introduction and motivation

Anthropogenic climate change (Weart 2008) requires a reduction in greenhouse gas emissions in order to achieve the 1.5 degree goal defined in the Paris Climate Agreement (UNITED NATIONS 2015). This requires national regulatory provisions to develop a target path with regard to emission reductions in relevant economic sectors. This development currently poses particular challenges for energy-intensive industries, such as the steel industry (Neuhoff et al. 2016). The long term resulting costs for the economy are strongly dependent on future human behaviour and related decisions on emission limits and adaptation measures (Klepper et al. 2017).

Due to the European Union's commitment to action resulting from the Paris Climate Agreement (cf. UNITED NATIONS 2015), the European Green Deal of net zero emissions until 2050 (European Commission 2019), neutralizing carbon emissions has arrived on everyone's agenda and is proposing major challenges (Qian et al. 2022). This results in economic risks and monetary additional burdens for companies in connection with climate change, which are explained below.

The European Commission established the EU Emissions Trading Scheme (EU ETS) to ensure that climate protection goals are achieved (European Commission). This emissions trading system, known as "downstream", relates primarily to plant operators who emit direct emissions into the environment and affects companies in the energy sector and energy-intensive industries. The aim is to reduce CO_2 emissions and thus achieve the climate targets set in Paris. Emissions trading is based on the cap and trade principle. The system on account of the idea that for every ton of CO_2 emitted, a company must submit a certificate for approval of the emission assessment on the environment and the number of certificates is capped each year. Part of the allowances will be allocated free of charge to the companies involved, while the remaining volume will be purchased at auction. The certificates in circulation are tradable. Companies can sell surplus certificates or purchase required certificates. The available CAP is further reduced every year, with the goal of reducing emissions by 43% by 2030 compared to 2005. (German Environment

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Agency 2021) Through this approach, the degree of technology used to reduce emissions is correlated with the resulting additional monetary impacts. Companies that pursue and actively implement such activities can thus gain competitive advantages. Although this emissions trading currently only applies to energy-intensive industries, such as steel production, a future extension to this area cannot be ruled out due to the major influence of the manufacturing industry.

Due to its global impact, climate change defines an extensive field of conflicts for the processing industry, which is reflected in a variety of challenges. In addition to the legal regulations, the framework conditions within economic activities are changing more and more intensively. This concerns on the one hand the financial economy, and on the other hand the goods economy with regard to the expansion of purchasing decision criteria in the context of climate change. As part of the German government funded research project "CRed", the relationship between climate reporting and the assessment of a company's value was investigated, with the result that companies with particularly high emissions have lower market values. In this framework companies that actively reduce emissions through optimization processes are considered to have a more futureproof, which leads to a better valuation on the capital market. (Schiemann et al. 2019)

The growing ecological awareness among the population confirms the relevance of taking into account one's own environmental impact through economic activities. Addressing climate protection in connection with business activities can result in competitive advantages, as purchasing decisions are increasingly made dependent on this, which can lead to benefits on the market. (Ahrend 2019)

Across all of the above challenges is a remaining CO_2 budget, which defines the amount of emissions still available up to the defined maximum limit. Thus, according to the current state of research, the 1.5-degree target defined in the Paris Climate Agreement is directly related to a remaining CO_2 budget. This remaining budget is regularly recalculated by the Intergovernmental Panel on Climate Change (IPCC) and provides information on the remaining amount of CO_2 emissions worldwide that is still available for an average global warming of 1.5 degrees. Since the beginning of 2020, around 400 Gigatons of CO_2 remain to achieve the goals of the Paris climate agreement. (Allan et al. 2021)

In order to implement national climate protection targets, national budgets will have to be derived in the future, which will make it possible to achieve climate neutrality in the global economy by 2050. (Hornberg et al. 2020)

In summary, multidimensional challenges for companies due to climate change can be identified. At present, it is difficult to predict how these challenges will develop in the future, but it is not possible to predict the general need for action. This is clearly motivated by the remaining global CO_2 budget, which will be consumed over time. Many companies have recognised the situation and set themselves ambitious goals with regard to achieving CO_2 neutrality. An important step is the detailed analysis of CO_2 emissions across the entire supply chain, differentiated by Scopes 1, 2 and 3 (Tamayao et al. 2014). For this purpose, e.g. Siemens AG uses inhouse IT tools to make the individual CO_2 footprint of specific products respectively customer orders transparent. These tools are based on Internet of Things (IoT) and blockchain technologies.

In addition to the transparency of CO_2 emissions along supply chains, carbon capture sinks are very important for success in the context of CO_2 neutrality. The University of Technology Sydney (UTS) can be considered as a pioneer of technical aquatic sinks. The sinks are photo-bio-reactors in various designs and dimensions for the production of microalgae on an industrial scale. In terms of photosynthesis and CO_2 absorption, algae are many times more efficient than forests. The biomass produced serves as a raw material for numerous products that enable the permanent binding of CO_2. The special feature of the UTS laboratory setup for algae production is its design as a highly automated cyber-physical system. The growth of biomass and the associated CO_2 absorption can be recorded in real time or, alternatively, accurately predicted using machine learning models. The IoT middleware enables a direct, virtual coupling of aquatic sinks with globally distributed CO_2 sources and serves as a proof-of-concept for future blockchain connectivity. In this paper, the implementation of the described approach based on a commercial IoT platform will be discussed.

2. The relevance of carbon sinks

Industrial production will always generate CO_2 emissions due to the associated manufacturing and logistics processes. For a product carbon footprint (PCF) neutral production it is therefore essential to compensate these emissions. For this purpose, sinks are needed that storage CO_2 emissions in the amount of the source emission from the atmosphere in order to keep the earth's climate in balance (Lucius et al. 2005). It should therefore be noted that the sinks described below only capture CO_2 from the atmosphere. Other greenhouse gases, whose climate impact is measured in CO_2 equivalents, are not removed from the atmosphere in this process.

Currently, suitable ecosystems are divided into terrestrial and aquatic sinks. Terrestrial sinks include forests, for example. These take up a particularly large amount of CO_2 from the atmosphere during the growth phase. In this development phase there is a high demand for nutrients and thus a corresponding CO_2 withdrawal from the environment. This CO_2 is stored as biomass in the form of wood. (cf. Gleixner et al. 2009; Meyer et al. 2021; Nord-Larsen et al. 2019) However, the sink capacity of forests varies greatly depending on climatic conditions and the tree species used. Furthermore, CO_2 storage is limited by the life cycle of a tree. By decomposition of the biomass of a tree, the bound CO_2 can be partially released back into the atmosphere. In addition, the high area requirement and the difficult to calculate performance of absorption due to the open environment of a forest are further disadvantages (Fuss et al. 2018). Extending this, wildfires can contribute to a large amount of CO_2 being emitted at the same time, significantly shortening the sequestration period. (Luick et al. 2021)

In general, sink technologies of any kind must be as accurately calculable as possible in order to measure their impact in the context of source-sink coupling and to ensure that the right amount of CO_2 is captured. The question is whether the entire CO_2 emission can be compensated or whether the emissions in the atmosphere can be reduced by using a selected technology. This requires well parameterizable and controllable solution approaches, which are to be researched and developed in the future. One possible approach is being pursued by the UTS research group in the field of sink technologies.

Aquatic sinks are available as an alternative to terrestrial sinks. These include algae, which according to current research represent a potential ecosystem for targeted carbon capture. Due to the high photosynthesis performance of algae, a significantly higher efficiency can be achieved compared to forests. On the one hand, the lower area requirement and the strong growth are decisive. In addition, the biomass produced can be used as a raw material for various products. These include, for example, house construction, which results in an equivalent CO_2 bonding time due to the long life cycle of a house. (Rossignolo et al. 2022) In connection with the approach of connecting sinks via IoT described here, the use of algae offers the advantage of a closed system, which enables corresponding monitoring and verification of the sink performance and makes it available in the overall system.

3. The Estainium Association

The complexity of enabling production with a neutral PCF requires interdisciplinary collaboration between industry and academia to create a holistic approach including stakeholders such as customers, suppliers, certification service providers and manufacturers. The Estainium Association (EA) was founded to enable these stakeholders to work together to contribute to sustainable development. The overall goal is to drive industrial decarbonization holistically in a precompetitive, cross sector and cross functional ecosystem that includes universities, SMEs and large companies alike. (Estainium Association 2022)

For this purpose, digital technologies are used to demonstrate scientifically sound ways of identifying, reporting, continuously documenting and compensating for climate negative impacts. There is a particular focus on the exchange of trusted carbon footprint data using blockchain technology and the necessary IoT connectivity. This integrates not only CO_2 sources, but above all certified CO_2 sinks into the platform to be developed. Terrestrial and aquatic sinks, without which the targeted CO_2 neutrality could not be achieved, must be connected in a clearly traceable and tamper proof manner.

The research work of EA takes place within three working groups, which deal with different technological challenges of platform development. The technical background of these is briefly explained below.

- Technology and Infrastructure: Within this working group, solutions for the comprehensive exchange of Environmental Social Governance (ESG) and PCF data along a supply chain are being developed. The overall goal is to create interoperability through common technologies and associated standards and thus to establish a basic infrastructure based on IDunion or GAIA-X, for example. These are architectures for a trusted data infrastructure.

- Standards and Norms: In the second working group, overarching standards and norms are developed, which serve as a basis for the implementation of interfaces between different actors in other working groups. In detail, the work includes the definition of metastandards, manuals and exchange formats for ESG data and the assurance of the interoperability of PCF standards. In addition, approaches for the meaningful and coordinated integration of sinks will be developed.

- Carbon Capture, Use, Storage & Compensation: Within the third working group, the creation of an overarching marketplace is pursued, which transparently presents PCF data and simultaneously enables an exchange of trusted carbon footprint data using blockchain technology. The entire functionality of this marketplace will be provided in the Siemens software SiGreen and will enable, the presentation and exchange of PCF data and the request for certification services for trusted carbon sink services within supply chains. To ensure interoperability, SiGreen is being developed as a web application. In addition, it is planned to develop recommendations for legislation within this working group, which will define the legal framework for the handling of corresponding data and linkages between sources and sinks.

UTS, as a designated founding member of the EA has been part of the third working group since the beginning of the association's work. The goal is to use this sink technology as an efficient tool for carbon sequestration by creating a controlled environment. By linking it to IoT, a valuable contribution can be made to capture carbon in the long term and to reuse the biomass produced as a raw material for numerous products that enable the permanent storage of CO_2.

4. Product carbon footprint transparency

In order to be able to produce products in a CO_2 neutral way in the future, a lot of scientific questions have to be answered regarding the use of sinks to compensate for CO_2 sources such as production. A relevant aspect in this context is the extension of existing methods in the field of PCF allocation. In order to determine the capacitive demand of future carbon capture systems it is necessary to develop accurate methods to determine the real PCF.

According to the current state of technology and research, the environmental impact of products is assessed using the Life Cycle Assessment (LCA) method (ISO 14040; ISO 14044). This method is based on the consideration of the product life cycle and enables the calculation of the resulting environmental impact of a product by using a standardized procedure. LCA can also be used to analyze subprocesses of the life cycle. These studies, known as Simplifield Life Cycle Assessment (SLCA), can, be used exclusively to analyze the production in order to determine its influence on the PCF (cf. Hochschorner/Finnveden 2003).

The LCA calculation of CO_2 emissions is based on statistical data, which is why this method can be described as static. However, especially in the production environment, dynamic aspects have a great influence on production processes. For this reason, there are already some approaches that extend LCA to include dynamic aspects of production. These methods, known as DES-LCA, combine LCA with the Discrete Event Simulation (DES) method. In this way, simulation data of a production area to be investigated are used instead of static data in the context of a classical LCA analysis.

The variances between LCA and DES-LCA have been investigated by Lindskog et al. 2011. The differences between a static SLCA compared to a DES-(S)LCA approach have been compared based on an industrial use case. As a result, the authors show a deviation of about 60% between the two methods in terms of the resulting environmental impact of a product. This discrepancy is largely due to the variation in electricity consumption between static and dynamic process mapping. This highlights the relevance of dynamic approaches and the resulting need for optimization.

At this time, existing DES-LCA approaches only refer to predefined use cases with different accounting framework conditions. Accordingly, the considered PCF influences within production processes are not uniformly defined, since the calculation is strongly dependent on the selected mapping level of the DES method (cf. Sproedt et al. 2015; Brondi and Carpanzano 2011). The Institute for Production Systems from the Technical University of Dortmund is currently researching the development of an interoperable calculation rule in the environment of the processing industry. The goal is to enable a holistic PCF calculation by means of dynamic methods and to develop measures for a PCF reduced process management based on this. This creates the potential for accurate and consistent balancing of the PCF, regardless of the existing product system. In addition, this new approach enables the identification of PCF drivers which can be reduced by an adapted process management and thus products with a reduced PCF can be produced.

With the transparency gained in this way, it will be possible in the future to precisely measure the sink requirement and, based on this, to make a statement as to whether the sink technology used will compensate for or reduce global emissions. In addition, a choice can be made between different sink technologies that are suitable for the purpose. This is of crucial relevance for the future balance of the global climate and the associated production of PCF neutral products. In the long term, these research results will help to determine the real need for carbon capture processes and thus to create a CO_2 neutral production environment.

5. Cyber-physical microalgae farms as a technology for global sinks

Microalgae have proven to be a promising product that can be used in many applications and construction material. In any case, their growth depends on a continuous supply of CO_2, which implies that their production constitutes a natural sink of CO_2. While the demand for microalgae is growing, commercial production is hindered due to their evolutionary history and great biological and physiological diversity (Rawat et al. 2013). The Centre for Advanced Manufacturing of UTS operates an Industry 4.0 laboratory for algae production on an industrial scale. The challenges involved in upscaling the production are investigated by applying promising Industry 4.0 technologies.

The laboratory features two industrial photobioreactors (PBR) for microalgae cultivation and a harvesting machine (see Figure 1). The Subitec LS28 (cf. SUBITEC 2021) harvesting machine has a working volume of 28 litres and the Industrial Plankton 1250L (cf. Industrial Plankton 2022) PBR has a capacity of 1250 litres. While the LS28 can be operated independently, it is used to accelerate the cultivation within the PBR1250L through an increased initial biomass inoculation. The customized built harvest machine is designed to process 350 litres of algae media per usage.

To guarantee the supply of the algae with sufficient CO_2, an air stream enriched with CO_2 is regularly fed into the reactors. The CO_2 is taken from gas cylinders, which can store gas from any potential CO_2 source. In order to measure the CO_2 absorption of the microalgae during cultivation, the PBR has been enhanced with a sensor system consisting of a mass flow controller in the gaseous intake (constant CO_2 percentage provided by PBR control) and a concentration sensor at its output.

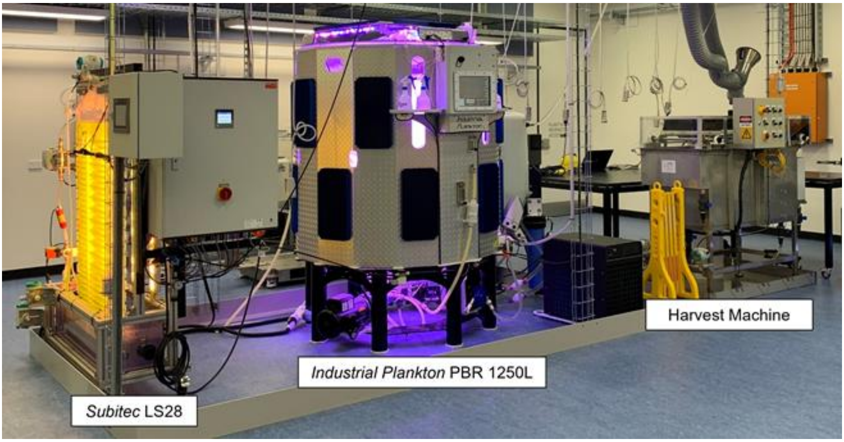

Figure 1: Setup of the UTS CAM Industry 4.0 algae laboratory

The physical components are complemented and connected by an IoT and data science architecture (see Figure 2). All systems are monitored and controlled by a Siemens hardware and software suite, including MindSphere and an S7-1500 acting as master PLC. In addition, a parallel architecture was designed based on Node-RED, MySQL, and Grafana and incorporated as an alternative to MindSphere, as an exploratory, low cost alternative for specific use cases. Rapidminer serves as data science platform in both contexts.

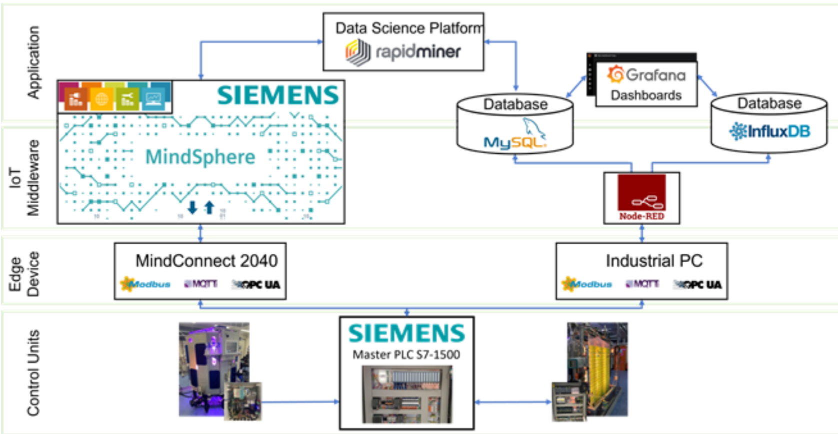

Figure 2: UTS CAM Industry 4.0 algae laboratory IoT/data science architecture

A digital twin is currently being developed to simulate, predict, and optimize the system across the production lifecycle to enable upscaling of algae production.

This will provide an improved understanding of algae behaviour and characteristics in an industrial setting and ultimately enable cost and time efficient algae production.

6. Proof-of-Concept based on algae farming

The inbuilt Industry 4.0 technology provides the foundation for traceability of neutralised emissions via blockchain technology to securely connect carbon source and sink. A current focus of the work is on ensuring accurate calculation of the CO_2 absorbed by the microalgae. This can be measured in several ways using the available sensors on the photobioreactor system. For example, measuring the gas flow of both CO_2 in and out of the system allows the net CO_2 absorbed to be determined. Weighing the total mass of algae produced also allows the absorbed CO_2 to be extracted in another way. The dual approach to CO_2 absorption calculation is deliberate, since it provides some redundancy in the system. This means that if one (set of) sensors fails, CO_2 absorption can still be recorded. The consistency and reliability of CO_2 measurement by these two means is currently being investigated. At the production site, accurate estimation of CO_2 production is not a focus of this work and is a more mature topic of research. However, it is vital that the CO_2 being offset is accurately accounted. Both the CO_2 production and absorption data are being integrated within extensions of existing Siemens software platforms as part of this project. This includes incorporation within MindSphere's Energy Manager, and enabling a connection according to the EA standards. Figure 3 shows an example of how carbon emissions generated by a source in Germany could be offset by the UTS CAM Industry 4.0 algae laboratory.

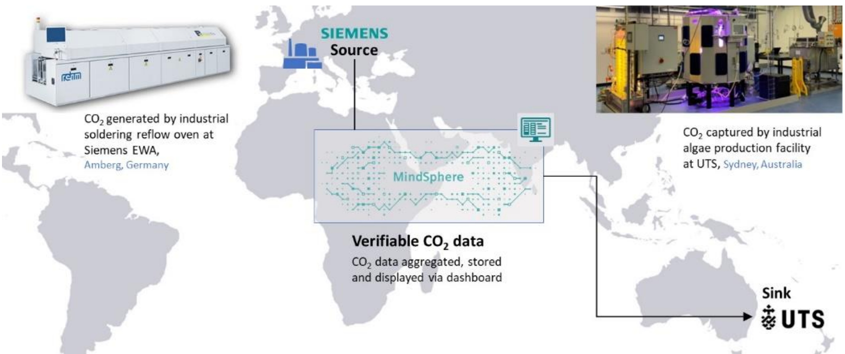

Figure 3: Virtual CO2 pipeline from source to sink

7. Conclusion and outlook

The demonstrated proof of concept represents an efficient approach to reducing CO_2 emissions, which holds out the prospect of a high reduction potential through the use of algae. Due to its full integration into the industry 4.0 environment, the concept enables a connection to technologies for the trustworthy certification of CO_2 data and the sources as well as sinks can be organized in a decentralized manner, which does not limit the strategic options for companies compared to alternative sink technologies. In summary, the described approach offers the potential for end-to-end CO_2 reduction, starting with the source, continuing with data verification, and ending with the technology of a CO_2 sink described in this paper. In doing so, the project can be developed in an overarching manner by integrating it into the Estainium network and creating a holistic contribution to the reduction of CO_2 emission. This paper describes the current state of development in the context of a proof of concept. A current focus of the work is on ensuring accurate calculation of the CO_2 absorbed by the microalgae in a reliable and consistent way, including introducing redundancy in case of sensor failure. In further investigations, the research work is to be centered on the optimization of algae production and to measure the achievable scaling effects. Thereby, methods of simulation and data science support the determination of an optimal operating point. The next step is to embed the data into the SiGreen environment and thus connect the aquatic sink with regard to functionalities such as requesting, calculating and sharing trustworthy PCF data. For this purpose, both the CO_2 production and absorption data will be integrated within extensions of existing Siemens software platforms, such as MindSphere's Energy Manager and a connection of the sink according to the Estainium standards will be enabled.

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