H2020-FNR-2020-2
LC-FNR-13-2020

CREATING ADDED-VALUE CHEMICALS FROM BIO-INDUSTRIAL CO_2 EMISSIONS USING INTEGRATED CATALYTIC TECHNOLOGIES

D6.1 – Report on LCA and LCC: Screening test and first recommendations

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Date: 31/05/2024

This deliverable, D6.1 leaded by DAN*NA, presents the comprehensive Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) of the CATCO2NVERS project technologies. It encapsulates the methodologies, analytical processes, and findings from the evaluation of the environmental and economic impacts of novel waste-CO_2 valorization technologies.

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101000580.

Project details			
Project acronym	CATCO2NVERS	Start / Duration	1/05/2021
Topic	LC-FNR-13-2020	Call identifier	H2020-FNR-2020-2
Type of Action	RIA	Coordinator	FUNDITEC
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Website	https://catco2nvers.eu/		

Deliverable details			
Number	6.1		
Title	Report on LCA and LCC: Screening test and first recommendations		
Work Package	6		
Dissemination Level	PU	Nature	PUBLIC
Due date (M)	M32	Submission date (M)	M38
Deliverable responsible	DAN*NA	Contact person	n.marcela@artificialnature.com (DAN*NA)

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Final review and quality approval				

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Acronyms and abbreviations

BFD	Block flow diagram
CCFAMES	Cyclic Carbonated Fatty Acid Methyl Esters
CCU	Carbon Capture and Utilization
DCP	Dissemination and Communication Plan
DOA	Deed of Agreement
EC	European Commission
EU	European Union
FDME	Furan Dicarboxylic Methyl Ester
GA	Glyoxylic Acid
GP	General Public
GWP	Global warming potential
ISO	International Organization for Standardization
LA	Lactic Acid
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life cycle inventory
OEM	Original Equipment Manufacturer
OPEX	Operational Cost
PFD	Process flow diagram
PM	Policy Makers
R&D	Research and Development
SC	Scientific Community
SI	Software industry
TEC	Technology - Placeholder for specific technology names
TM	Trade Media
TRL	Technology readiness level
USD	United States Dollars
WP	Work Package

Executive summary

This document serves as Deliverable D6.1 for the CATCO2NVERS project, corresponding to the comprehensive Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis of innovative technologies developed for the valorization of waste-CO_2. This deliverable synthesizes the work completed up to month 36, providing a pivotal evaluation of the environmental and economic sustainability of five distinct catalytic methods researched and developed within the project framework.

The CATCO2NVERS project, with its core objective of transforming waste-CO_2 into valuable products, has reached a crucial juncture by month 36. At this stage, a series of screening tests has been conducted, offering preliminary data that guide the LCA and LCC analyses. These analyses adhere to the rigorous guidelines set forth by ISO standards (ISO 14040 & 14044 (2006)), ensuring a robust assessment. The LCA examines key environmental impact categories such as global warming potential, ecotoxicity, and resource depletion, while the LCC at this stage focuses on the economic viability by scrutinizing the expenditures associated to the raw material and energy consumption of each of the technologies.

By month 36, the project has achieved significant milestones:

- **Screening Test Completion:** The screening tests conducted have yielded initial performance data for the CATCO2NVERS technologies, providing an early indication of their environmental and economic impact and potential.
- **LCA Insights:** Preliminary LCA results reveal the environmental advantages and challenges of each technology.
- **LCC Findings:** Early LCC analysis points to the potential cost savings and economic competitiveness of the CATCO2NVERS technologies.

The following general recommendations have been formulated based on the analyses conducted:

- **Optimization of Technology:** Enhance the efficiency and scalability of the CATCO2NVERS technologies to improve their environmental and economic profiles.
- **Policy and Stakeholder Engagement:** Engage with policymakers and stakeholders to ensure that the findings influence both regulatory frameworks and market dynamics.
- **Continued R&D Investment:** Focus on R&D investments to overcome identified barriers, and to achieve breakthroughs in both environmental and economic aspects, trying since the beginning to mitigate the identified risks related to the viability.
- **Strategic Collaboration:** Encourage collaborative efforts between industry, academia, and policymakers to accelerate the path to market for promising technologies.

In conclusion, Deliverable D6.1 encapsulates the complex balance between environmental responsibility and economic viability that defines the CATCO2NVERS project's vision. The document not only lays down a benchmark for current progress but also charts a course for the future actions needed to realize the project's ambitious goals. The subsequent phases of the project will continue to build upon these findings, refining the LCA and LCC analyses, and steering the technologies towards a sustainable and profitable implementation.

1. Introduction

The threats of climate change are being realized and addressed on a global scale. With unrelenting global carbon dioxide (CO_2) emissions, scientists and researchers are exploring ways to turn CO_2 into valuable resources. This concept is known as "Carbon Capture and Utilization" (CCU). European chemical industries are beginning to lead the way in reducing their carbon footprint by adopting these CCU technologies, which will also work to create new business opportunities and jobs. The embracement of CCU technologies will work to advance Europe's ambitious goal of being carbon neutral by 2050 (European Commission, 2024). These CCU technologies will be used to the CO_2 from two bio-based industries and utilize catalysts to transform the CO_2 into many different value-add chemicals. The chemicals that CATCO2NVERS is focusing on include the following: Glyoxylic Acid (GA), Lactic Acid (LA), Furan Dicarboxylic Methyl Ester (FDME), Cyclic Carbonated Fatty Acid Methyl Esters (CCFAMEs) and Bio-Methanol. These chemicals are commonly used in the chemical, cosmetics, and plastic industry. To better understand the environmental performance of these CCU technologies, a life cycle assessment (LCA) was conducted. The LCA will raise any flags, signaling potential obstacles for reaching the desired environmental goals, allowing for flexibility in readjusting research plan to meet the goals. After checking the results, relevant conclusions and recommendations will be drawn.

2. General Description of the Work

The CATCO2NVERS project focuses on transforming waste carbon dioxide (CO_2) from bio-based industries into valuable chemical products using innovative catalytic technologies. This deliverable presents the first recommendations based on a comprehensive Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) analysis at a lab scale. These assessments evaluate the environmental and economic impact of several catalytic processes that aim to convert waste-CO_2 into useful chemicals such as Glyoxylic Acid, Lactic Acid, Furan Dicarboxylic Methyl Ester, and others. These chemicals have widespread applications in cosmetics, plastics, and other industries.

The goal of this project is to contribute to Europe's carbon neutrality goals by developing sustainable and economically viable technologies (European Commission 2019).

The data for each technology was collected through a series of meetings with the project partners who are developing the technologies, as well as the deliverables submitted in this project. These meetings helped ensure we gathered the necessary information to calculate as accurately as possible the mass- and energy balance and evaluate the costs and environmental impacts involved.

The technology-specific mass and energy balance and costs are based on lab-scale. Since this data comes from lab experiments, there is a certain level of uncertainty in the results. Lab-scale experiments often don't perfectly reflect real-world production conditions, and some of the costs may change when the processes are scaled up for commercial use. However, despite these uncertainties, we were still able to identify some general trends and findings across all the technologies being developed. Since the underlying data is based on lab-scale data, this deliverable does not include a comparison with current state-of-the-art technologies for the production of the targeted chemicals. Such comparison would be unfair at the current stage, as lab-scale experiments are not energetically optimised. Moreover, lab-scale experiments often focus on proof-of-concept, meaning that mechanisms and influences are studies to identify optimal conditions, however reactants may be added in surplus to avoid limitation due to the reactants.

3. LCA and LCC Overview

This section should explain the methodologies used for assessing both the environmental and economic aspects of the technologies being developed in the CATCO2NVERS project.

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a scientific method used to evaluate the environmental impacts of a product or technology throughout its entire life cycle, standardised in ISO 14040 and ISO 14044 (ISO 14040, ISO 14044). In this case, we assess how the five catalytic processes developed within CATCO2NVERS affect the environment, from the collection of CO_2, through processing, to the final chemical product targeted in the project. As this deliverable focus on production processes currently being developed, and therefore at a low TRL, a screening LCA has been conducted. A screening LCA aims to identify the hotspots of the production process, in order to optimise the production process during the further development. As the TRL of the processes are low, most data has been obtained from lab-scale experiments, which has been complemented with assumptions, expert judgement and literature when necessary. An example of data obtained from literature is the energy consumption of centrifugation, which is assumed to be 5 kWh/m^3 (Abu-Shamleh, & Najjar 2020).

Key stages of the LCA:

1. **Raw Material Extraction**: In this stage, we evaluate the environmental impact of extracting raw materials needed for the catalytic processes. For CATCO2NVERS, CO_2 is captured from bio-industrial sources, reducing emissions that would otherwise contribute to climate change. Nonetheless, the capturing and potential purification of CO_2 requires energy and materials, which cause environmental impacts in its production.
2. **Production Process**: The core focus of the LCA is the environmental impact of the catalytic technologies themselves. This includes the energy required to convert CO_2 into chemicals, the materials consumed, and any byproducts or waste generated.

Due to the low TRL, the main focus of the LCA is to identify environmental hotspots, which can be optimised during the further development of the production process. As such, the system boundaries of the assessment are cradle-to-gate, meaning that the use- and end-of-life phase are not included in the assessment. For the purpose of identifying the environmental hotspots this is justified as the project develops chemicals which can be used in various applications, and thus have a wide range of uses and end-of-life possibilities. Moreover, the technology developers have a larger degree of control over the environmental impacts which occur due to the raw material production and the processing, compared to the use and end-of-life. Finally, the uncertainty associated with these two life cycle stages is higher compared to the uncertainty related to the production processes. In the screening LCA, background data from EcoInvent has been used (Warnet et al. 2016).

The energetic inputs are modelled using current available technologies, which are largely based on the consumption of fossil resources. As such, the electricity production is based on the average European electricity grid. In the final deliverable, the technologies will also be evaluated using renewable electricity. However, in the current deliverable, it was chosen not to assess these results in order to identify the impact of energy sources more easily. The use of wind-, solar- and hydroelectricity are associated with low impacts on climate change, however renewable electricity will remain a scarce resource over the next decade or two. As such, it remains important to develop energy efficient processes. When the LCA would include the use of renewable electricity, the environmental impact of the electricity use will be small, regardless of the quantity used. as a consequence, it is more difficult to evaluate the energy efficiency from the environmental impact results.

Environmental Impact Categories:

In assessing the environmental performance of the CATCO2NVERS technologies, we identified several key environmental impact categories. These categories help quantify the environmental burden of each process, focusing on critical aspects such as emissions, resource use, and energy consumption.

- **Global Warming Potential (GWP)**: This category measures the total greenhouse gas emissions produced by each technology, expressed in CO_2-equivalents. It is a crucial indicator for understanding how much each process contributes to climate change. A lower GWP means a reduced impact on global warming.

- **Resource Depletion**: This metric evaluates the depletion of non-renewable resources, including fossil fuels, minerals, and other finite materials. Processes that rely heavily on non-renewable resources are less sustainable, and this indicator helps identify areas where renewable alternatives can be introduced.
- **Energy Consumption**: Energy is a significant contributor to both environmental and economic impacts. This category assesses the total energy required for each process, distinguishing between renewable and non-renewable energy sources. Reducing energy consumption and increasing the use of renewable energy are key strategies for minimizing environmental harm.

These categories, along with **17 indicators**, provide a comprehensive view of the environmental performance of the catalytic processes developed in the project. The impact assessment method used is the Environmental Footprint 3.1, recommended by the European Commission (European Commission, 2021)

The goal of the LCA is to identify the **environmental hotspots**—areas where the processes have the most significant negative impact—so they can be optimized in future development to enhance sustainability. Apart from identifying the hotspots, recommendations to decrease the environmental hotspots are also made.

Life Cycle Costing (LCC)

For the economic evaluation of the CATCO2NVERS technologies, we selected key cost categories that provide insight into the financial feasibility of each process. Focusing on the most critical cost factors, we have chosen to assess the following:

- **Raw Material Costs**: This category covers the commercial prices of the raw materials required for the synthesis of the targeted chemicals. Since raw materials represent a significant portion of the total costs, particularly for novel catalytic processes, understanding their cost dynamics is essential for determining the economic competitiveness of each technology. The selection of cost-effective and sustainable materials is vital to improving the economic viability of the processes.
- **Energy Consumption**: Energy usage is a major operational cost, especially for processes that require high levels of electricity for equipment like reactors, pumps, and separation units. This category evaluates the costs associated with electricity usage, calculated based on the power consumption of the main equipment involved in each process. By identifying areas where energy consumption is particularly high, cost-saving opportunities can be explored, including the potential switch to renewable energy sources to further reduce costs.

By focusing on these two critical LCC categories, we can derive a clear understanding of the economic barriers and opportunities associated with each technology. These findings will guide future optimizations to improve the cost-efficiency of the CATCO2NVERS processes while maintaining their environmental benefits.

4. Conclusion

In conclusion, the initial screening of the technologies within the CATCO2NVERS project indicates that while each technology shows potential, further optimization is required to balance environmental sustainability with economic viability. Technologies like TEC1 (Glyoxylic Acid) and TEC5 (Bio-methanol) show potential environmental advantages but encounter challenges in achieving cost-effective scalability, especially in the absence of direct comparisons with conventional Glyoxylic Acid or methanol production methods in the current LCA data. Recommendations include further R&D investments to overcome technological barriers, engagement with stakeholders for policy alignment, and fostering collaboration between academia and industry to ensure market integration of these technologies. These early findings set the foundation for refining and improving the technologies in the next phases of the project.

TEC1 demonstrates the potential for converting CO_2 into valuable Glyoxylic Acid, but energy consumption during the production process is a significant environmental challenge. Key areas for improvement include reducing the energy required for electrochemical conversions and exploring ways to recover materials used in the process. Enhancing the efficiency of material recovery could lead to significant reductions in waste and emissions. Further development should focus on optimizing the energy efficiency of the process and exploring renewable energy options to minimize its environmental footprint. The use of renewable energy would minimise the environmental impacts of the energy used in the processes; however renewable energy will remain a scarce resource for the next decade. Therefore, it is important to optimise the energy efficiency of the process.

For TEC2, environmental impacts are primarily driven by the inputs used in the lab-scale production, particularly in the production of enzymes. Future efforts will focus on reducing the need for excessive inputs, such as chemical buffers, and optimizing the conversion process. Increasing the reuse of enzymes and improving the efficiency of the reaction system will be key strategies to make the process more sustainable. Additionally, investigating alternative uses for by-products could enhance both the environmental and economic performance of the technology. Enhancing the concentration of substrates and products to minimize downstream processing costs is a key area for development. Engagement with stakeholders and industry experts will be crucial for developing cost-effective scaling solutions.

TEC3 focuses on producing FDME, a bio-based chemical with promising industrial applications. Current environmental challenges include the use of certain raw materials and the production of chemical by-products. Efforts to improve the reaction yield and explore recycling or repurposing of by-products will be crucial to lowering the overall environmental impact. Future work will focus on refining the production process to make it more efficient and environmentally friendly. To improve the financial feasibility, it is recommended to investigate the recovery and recycling of expensive reactants, and to optimize reaction conditions to increase yield.

In TEC4, the catalyst used in the reaction plays a critical role in the overall environmental impact. Improving catalyst efficiency and extending its usability are key to making the process more sustainable. Additionally, the environmental impact of raw materials needs further consideration, particularly in terms of sourcing renewable feedstocks. Optimizing these aspects will help lower the process's environmental footprint and improve its potential for industrial application. Increasing the reusability of catalysts and optimizing their performance are key to reducing operational expenses. Additionally, sourcing renewable, cost-efficient feedstocks can help mitigate the high cost of raw materials.

TEC5 focuses on converting CO_2 into bio-methanol, which has potential as a platform chemical and renewable fuel. The primary challenge identified is the high energy requirement of the process. Future improvements will focus on increasing energy efficiency, using renewable energy sources, and enhancing the overall process performance. Optimizing the reaction to make better use of inputs will also be a priority, helping to reduce environmental impacts and improve the technology's scalability.

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6.Access to Full Version

The full version of this deliverable is available with restricted access and can be accessed through the following link: DOI: 10.5281/zenodo.13943999. Please note that access is limited to authorized users only.