Advanced Carbon Capture for steel industries integrated in CCUS Clusters

Innovation Action

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No 884418.

D4.11 Method to address technology scaling (Task 4.3.1)

Work Package: 4
Due date of deliverable: month 30
Actual submission date: October 6th 2022
Start date of project: 1st April 2020 Duration: 48 months
Lead beneficiary for this deliverable: SKU
Contributors: Thomas Hennequin, Rosalie van Zelm (SKU)
Reviewer: Jebin James (TNO)

Dissemination level: PU

PU	*Public*
CO	*Confidential, only for members of the consortium (including Commission Services)*
CI	*Classified*

Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

Executive summary

This report constitutes deliverable D4.11 of the C^{4}U project: method to address technology scaling. It is related to task 4.3.1 where the goal is to quantify the environmental impact of an industrial implementation of the C^{4}U carbon capture and sequestration (CCS) technologies. Process data representative of high TRL implementations needs to be modelled to do so. D4.11 aims to develop a methodology that allows for building such an inventory and in turn to conduct a prospective life cycle assessment.

The framework developed by van der Hulst [1] was chosen as the starting point to develop the methodology used to model the high TRL life cycle inventory (LCI) and conduct the prospective life cycle assessment (LCA). Two main steps are suggested: TRL definition and process scaling, where process changes, size scaling, and process synergies are identified and modelled. Expert input will be used as much as possible to obtain a robust and realistic inventory. Scenario analysis should be used, notably to model the impact of future electricity mixes. Additional methodological inputs from the literature will be used to supplement the van der Hulst framework such as TRLs definitions [29] and learning curves [24] developed specifically for CCU. The theoretical framework is presented in section 4 of this report.

To gather that expert input, regular meetings with C^{4}U's WP3 have been and will continue to be organized. The most important elements needed to build a CASOH or DISPLACE prospective LCI are (1) an understanding of the general overlay of the high TRL integration, (2) the electricity and heat consumption, (3) the utilities flows, and (4) the main materials used for the production of the equipment. It was found that all these key elements can be obtained from WP3's models. The collaborative effort and the main findings are presented in section 0 of this report.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

1. Version log

Version	Date	Released by	Nature of Change
0.1	29/09/22	T. Hennequin (SKU)	First draft
0.2	04/10/22	T. Hennequin (SKU)	Integrated review feedback from Jebin James
1.0	06/10/22	SKU and UCL	Final version

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

2. Definition and acronyms

Acronyms	Definitions
CASOH	Calcium Assisted Steel-mill Off-gas Hydrogen
CCS	Carbon Capture and Sequestration
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Utilization and Storage
DISPLACE	High temperature sorption-DISPLACEment process using hydrotalcites for CO_2 sorption and recovery of steam
IAM	Integrated Assessments Model
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
pLCA	Prospective Life Cycle Assessment
TRL	Technology Readiness Level

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

3. Introduction

The iron and steel industry is a key economic and social driver, providing essential commodities in a variety of areas. However, 1.83 tons of CO_2 are emitted on average per ton of steel produced in 2018, resulting in about 8% of the global anthropogenic emissions [2]. Given the urgency of mitigating these emissions, a portfolio of viable CO_2 capture technologies must be developed and tested to a high Technology Readiness Level (TRL) to identify the most cost-effective and energy-efficient integration solutions. The C^4U project, a multidisciplinary initiative, addresses all the major elements for successful CO_2 capture integration in the iron and steel sector. It aims to elevate two emerging CO_2 capture technologies, DISPLACE and CASOH, with the potential to eliminate up to 94% of the CO_2 emissions in a steel plant.

This report constitutes deliverable D4.11 of the C^4U project: method to address technology scaling. It is related to task 4.3.1 where the goal is to quantify the environmental impact of an industrial implementation of the C^4U carbon capture and storage (CCS) technologies. The first step towards that goal was already conducted in D4.10, which presented the Life Cycle Assessments (LCAs) of the pilot implementations of the DISPLACE and CASOH C^4U technologies at TRL 7. Process data representative of high TRL implementations needs to be modelled for the next step. D4.11 aims to develop a methodology that allows for building such an inventory.

LCA is a methodology used by researchers, companies, and decision-makers to holistically assess a product's or service's environmental impacts throughout its lifetime. It is a well-established and widely used framework, extensively standardized through ISO14040 and 14044 [3], [4]. In practice, it consists of an iterative process comprised of four main steps: 1) the goal and scope definition, which sets the aim and limitations of the study, 2) the Life Cycle Inventory (LCI) construction listing all unit flows and processes needed throughout the system's life cycle, 3) the life cycle impact assessment where the LCI is converted into impacts in different categories, and 4) interpretation of the results.

LCA has been used to study the potential environmental benefits of CCS as well as Carbon Capture and Utilization (CCU) technologies [5]–[9]. It was shown that implementing CCS and CCU technological solutions leads to the mitigation of the climate change impact of the system studied. The effectiveness of that mitigation depends on the type of technology studied and how it was implemented. While a reduction of climate change impact was observed, it comes at the price of a burden-shift. That is, increases in other impact categories, specifically for impact on acidification and human toxicity [6], [9].

Prospective LCA, also called ex-ante LCA, is based on the well-defined LCA methodology. It allows an emerging technology to be modelled at a future, more-developed phase while it is still in early development [10] (see Figure 2). Environmental hotspots in the production process can be found early in the process design planning phase. Moreover, alternative techniques or products can be evaluated to propose a design with lower environmental impact [11]. Several

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

authors have proposed a framework for performing prospective LCA [1], [12]–[14]. Case studies showed that the environmental impact is reduced when emerging technologies are scaled from laboratory to industrial scale [15]–[17].

This activity aimed to develop a methodology to address technology scaling. To quantify the impact of high TRL implementation of CASOH and DISPLACE, corresponding high TRL LCIs of the two technologies need to be modelled. The methodology developed relies on two main elements: (1) the theoretical background and frameworks developed in the pLCA field (see section 4) and (2) a collaboration with members of the consortium who work towards a high TRL model from the techno-economic perspective (see section 0).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

4. Theoretical background

4.1. Processes descriptions

CASOH and DISPLACE are emerging carbon capture technologies that involve high-temperature gas-solid separation processes and use steel mill off-gases as input. Both processes are illustrated in Figure 1.

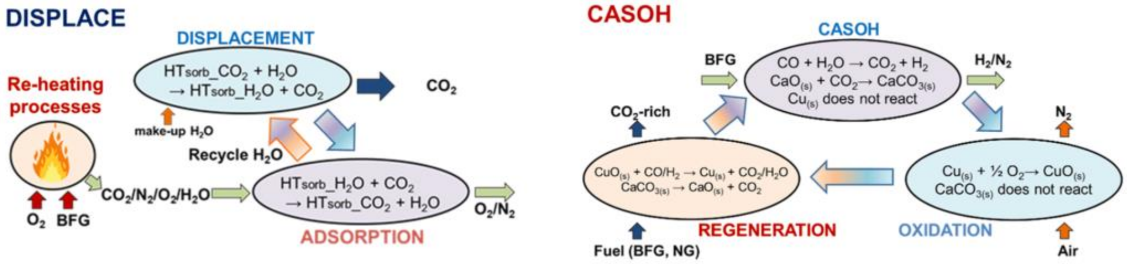

Figure 1 – Schematic representation of the DISPLACE and CASOH processes.

CASOH stands for Calcium Assisted Steel mill Off-gas Hydrogen production and transforms BFG into an H_2-rich gas separated from CO_2. High-temperature heat is also produced as a by-product. The process consists of three main stages: (1) the water-gas shift reaction enhanced by the carbonation of calcium oxide and catalyzed by Cu-based particles, (2) the oxidation of the Cu-based catalyst, and (3) the regeneration of the calcium oxide sorbent. At the pilot stage, intermediate heat removal stages are also required.

DISPLACE is a high-temperature sorption displacement process that recovers CO_2 from the flue of a steel mill's oxy-fuel burner. In an oxy-fuel burner, BFG is combusted with oxygen to provide heat for the reheating process. CO_2 is then separated from the resulting flue gas with adsorption using hydrotalcite. Finally, the CO_2 is displaced from the hydrotalcite with counter-current regeneration. Steam is recycled between the displacement and adsorption stages.

4.2. pLCA

Technological advancements are important to fulfil the demand for goods and services and economic growth. They can also contribute to minimizing environmental impacts and should be developed so that they contribute minimally to environmental impact. Assessments of their environmental impacts may be used to determine their potential and to help direct their development. Analyses that support early design changes are especially valuable as they can ultimately lead to significant environmental impact mitigation [11], [18], [19]. Life cycle assessment (LCA) is used to look retroactively at the impact of products, services, and technologies, including CCUS [5]–[9], [20], [21]. Prospective LCAs (pLCAs) are conducted to study the environmental impacts of emerging technologies [12], [15]–[17], [20], [22].

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

pLCA, sometimes referred to as ex-ante LCA, is based on the well-defined LCA methodology. Here, we follow the definition put forward by van der Hulst [1]: "an LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g., small-scale production), but the technology is modelled at a future, more-developed phase (e.g., large-scale production)". pLCA allows us to find environmental hotspots in the production process at an early phase of the industrial design planning. Moreover, alternative techniques or products can be evaluated to propose a design with lower environmental impact [11], [15]. Various case studies showed that the environmental impact is reduced when emerging technologies are scaled from laboratory to industrial scale [15]–[17]. pLCA has been applied to CCUS solutions as well [12], [20], [22].

LCA practitioners still face several challenges in conducting prospective studies. The design of emerging technologies is easier to change at low TRL, but it also is inherently uncertain. Consequently, an environmental impact assessment at that stage has high transformative power but is limited by that uncertainty [10], [23]. Moreover, the lack of primary data needed to conduct LCAs at low TRL is a widely recognized issue [11], [23]–[25]. This leads to difficulties establishing valuable case studies that can demonstrate the applicability of the developed frameworks [1], [26]. To mitigate those uncertainties, several authors have proposed a framework for performing prospective LCA [1], [12]–[14].

4.3. Framework used in C^{4}U

For the work to be conducted in C^{4}U, the framework developed by van der Hulst [1] will be used as a starting point. It is divided into three phases (see Figure 2):

1. Phase I: The current TRL of the technology is determined in order to identify the steps needed to reach a mature implementation. This belongs in the goal and scope step of a traditional LCA.
2. Phase II: The steps needed to reach the industrial TRL are modelled. Three types of steps are identified: (1) process changes, such as a change in equipment or materials used, (2) size scaling, which is mostly capacity scaling; and (3) process synergies, which is mainly minimization of waste streams. Those three items will be modelled in the life cycle inventory (LCI).
3. Phase III: Industrial learning and external developments are modelled. The former consists of the improvements in production observed after a technology enters the market, which can result from learning-by-doing, production line synergies, and production scaling. The latter are future external developments that can influence the technologies' production, such as a change in the electricity mix.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

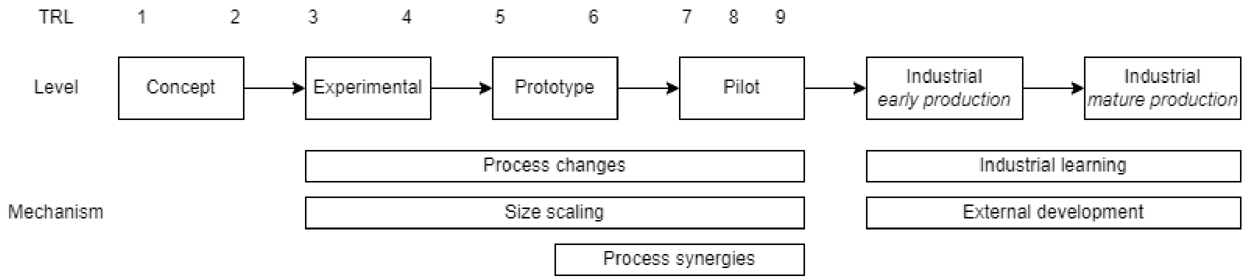

Figure 2 – TRL related to scale and mechanisms, adapted from van der Hulst et al. (2020)[1].

During Phase I, van der Hulst et al. advises to use the descriptions of TRL put forward by Gavankar et al. and Moni et al. [1], [11], [27]. Beyond those references, we will also use the definition proposed by the European Commission [28] and the various adaptations presented in the literature that are relevant for C^{4}U, e.g. for CCU [29] or the chemical industry [30].

For the case of C^{4}U, Phase II will be driven by models of the industrial scale, which will be used to yield an inventory. Expert input is key to obtaining a robust and realistic high TRL LCI [1], [19] and will be used whenever possible. As was done in D4.10, assumptions and literature will also be used to close the gap on any lack of data. Moreover, scenario analyses can explore best- and worst-case alternatives [12]. Uncertainty analyses can also be used to quantify the uncertainty inherent to assessment during the early design phase [22]. Both scenario and uncertainty analyses may be used for C^{4}U, depending on preliminary results.

In the case of C^{4}U, Phase III will be simplified by modelling external developments with scenario analysis. We will specifically focus on the future development of the electricity mix. Industrial learning may also be implemented using the framework proposed by Faber et al. which describes how learning curves can be adapted to emerging CCU technologies [24]. This simplification is needed because Phase III can be challenging to model. Modelling industrial learning is conditional on the availability of historical environmental data of the technology developed or a close substitute that can be used as a proxy. These data are typically scarce, even more so for CCUS, where large-scale implementations are lacking [24]. External developments are modelled by combining LCA and integrated assessments models (IAMs), which can be complex if time is limited. That step is sometimes replaced by a scenario analysis on the foreground system.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

5. Collaboration

To obtain expert input, collaborations are needed with the technology developers. The collaborative effort between work packages (WPs) 3 and 4 aimed to determine how the outputs of the techno-economic models developed by WP3 could be used as inputs for a high TRL pLCA. Specifically, according to the results presented in D4.10, the main components needed for a high TRL LCI are the electricity and heat consumption, the utilities flows, and the main materials used to produce the equipment. The general overlay of the industrial integration is also relevant, specifically any type of process synergy (e.g. re-use of heat).

The collaboration has been fruitful and has already led to several findings. The goal and scope of the work conducted in D4.10 were largely influenced by the first meeting on the 1st of December 2021. The functional unit was focused on the use of BFG as opposed to the capture of CO_2 to fairly account for the different capture points of CASOH and DISPLACE as well as the different levels of purity of output streams.

Future process synergies were also identified, those that will occur during the simultaneous use of CASOH and DISPLACE at the industrial scale. Excess heat from the CASOH system that currently needs to be removed could be fed into DISPLACE. This interaction will be modelled at high TRL in WP3 and will be consequently incorporated in the pLCA of DISPLACE and CASOH. Moreover, the CO_2 output stream of CASOH is less pure than DISPLACE's. Therefore, that output stream could be fed into DISPLACE which would then function as a purification unit. This would avoid the use of a cryogenic purification unit.

Most importantly, a data exchange protocol was established. According to the D4.10 results, the most essential elements needed to build a CASOH or DISPLACE LCI are (1) an understanding of the general overlay of the high TRL integration, (2) the electricity and heat consumption, (3) the utilities flows, and (4) the main materials used for the production of the equipment. More information on the process synergies outlined above is also important to model a fair representation of the high TRL implementation of CASOH and DISPLACE.

WP3 beneficiaries have indicated that all these data can be provided. This is the best case scenario for a pLCA LCI (see section 4.3), in which the use of expert input is fully maximized. We argue that this will lead to a representative and robust assessment of the environmental impacts of the C^4U technologies at high TRL. Typically, the exchange of data is an iterative process in which the inventory is supplemented with additional data and refined at each iteration. This will be kick-started in the next collaborative meeting, where the D3.2 and D3.3 results of WP3 will be presented.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

6. Conclusions

This report summarized the methodology that will be used to conduct the high TRL LCAs of the CASOH and DISPLACE pilots. It can be concluded that two main steps will be applied, namely, the TRL definition and the process scaling where process changes, size scaling, and process synergies are identified and modelled. Expert input will be used as much as possible to obtain a robust and realistic inventory. This methodology is based on the framework developed by van der Hulst [1] that will be adapted to the C^4U case notably by using scenario analysis to model the impact of future electricity mixes. Additional methodological inputs from the literature will be used to supplement the van der Hulst framework such as TRLs definitions [29] and learning curves [24] developed specifically for CCU.

To gather that expert input, regular meetings with C^4U's work package 3 beneficiaries have been and will continue to be organized. The most important elements needed to build a CASOH or DISPLACE LCI are (1) an understanding of the general overlay of the high TRL integration, (2) the electricity and heat consumption, (3) the utilities flows, and (4) the main materials used for the production of the equipment. It was found that all these key elements can be obtained from WP3's models.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

7. References

[1] M. K. van der Hulst *et al.*, “A systematic approach to assess the environmental impact of emerging technologies: A case study for the GHG footprint of CIGS solar photovoltaic laminate,” *J. Ind. Ecol.*, pp. 1–16, 2020.

[2] C. Hoffmann, M. Van Hoey, and B. Zeumer, “Decarbonization in steel,” *McKinsey*, 2020. [Online]. Available: https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel. [Accessed: 11-Apr-2022].

[3] ISO, “EN ISO 14044:2006 -Environmental management - Life cycle assessment - Requirements and guidelines,” 2006.

[4] ISO, “EN ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework,” 2006.

[5] R. Aldaco *et al.*, “Bringing value to the chemical industry from capture, storage and use of CO 2 : A dynamic LCA of formic acid production,” *Sci. Total Environ.*, vol. 663, pp. 738–753, 2019.

[6] R. M. Cuéllar-Franca and A. Azapagic, “Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts,” *J. CO2 Util.*, vol. 9, pp. 82–102, 2015.

[7] L. Petrescu, D. A. Chisalita, C. C. Cormos, G. Manzolini, P. Cobden, and H. A. J. van Dijk, “Life cycle assessment of SEWGS technology applied to integrated steel plants,” *Sustain.*, vol. 11, no. 7, 2019.

[8] K. de Kleijne, J. James, S. V. Hanssen, and R. van Zelm, “Environmental benefits of urea production from basic oxygen furnace gas,” *Appl. Energy*, vol. 270, no. May, p. 115119, 2020.

[9] D. A. Chisalita, L. Petrescu, P. Cobden, H. A. J. (Eric. van Dijk, A. M. Cormos, and C. C. Cormos, “Assessing the environmental impact of an integrated steel mill with post-combustion CO2 capture and storage using the LCA methodology,” *J. Clean. Prod.*, vol. 211, pp. 1015–1025, 2019.

[10] R. Arvidsson *et al.*, “Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA,” *J. Ind. Ecol.*, vol. 22, no. 6, pp. 1286–1294, 2018.

[11] S. M. Moni, R. Mahmud, K. High, and M. Carbajales-Dale, “Life cycle assessment of emerging technologies: A review,” *J. Ind. Ecol.*, pp. 52–63, 2019.

[12] N. Thonemann and A. Schulte, “From Laboratory to Industrial Scale: A Prospective LCA for Electrochemical Reduction of CO2 to Formic Acid,” *Environ. Sci. Technol.*, vol. 53, no. 21, pp. 12320–12329, 2019.

[13] B. Simon, K. Bachtin, A. Kiliç, B. Amor, and M. Weil, “Proposal of a framework for scale-up life cycle inventory: A case of nanofibers for lithium iron phosphate cathode applications,” *Integr. Environ. Assess. Manag.*, vol. 12, no. 3, pp. 465–477, 2016.

[14] N. Thonemann, A. Schulte, and D. Maga, “How to Conduct Prospective Life Cycle Assessment for Emerging Technologies ? A Systematic Review and Methodological

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

Guidance," no. Lcc, pp. 1–23, 2020.
[15] I. Bartolozzi, T. Daddi, C. Punta, A. Fiorati, and F. Iraldo, "Life cycle assessment of emerging environmental technologies in the early stage of development: A case study on nanostructured materials," *J. Ind. Ecol.*, pp. 101–115, 2019.
[16] M. Caduff, M. A. J. Huijbregts, H. J. Althaus, A. Koehler, and S. Hellweg, "Wind power electricity: The bigger the turbine, the greener the electricity?," *Environ. Sci. Technol.*, vol. 46, no. 9, pp. 4725–4733, 2012.
[17] I. De Marco, R. Iannone, S. Miranda, and S. Riemma, "An environmental study on starch aerogel for drug delivery applications: effect of plant scale-up," *Int. J. Life Cycle Assess.*, vol. 23, no. 6, pp. 1228–1239, 2018.
[18] S. Cucurachi, C. Van Der Giesen, and J. Guinée, "Ex-ante LCA of Emerging Technologies," *Procedia CIRP*, vol. 69, no. May, pp. 463–468, 2018.
[19] M. Villares, A. Işıldar, C. van der Giesen, and J. Guinée, "Does ex ante application enhance the usefulness of LCA? A case study on an emerging technology for metal recovery from e-waste," *Int. J. Life Cycle Assess.*, vol. 22, no. 10, pp. 1618–1633, 2017.
[20] M. A. N. Thonemann, "Environmental impacts of CO2-based chemical production: A systematic literature review and meta-analysis," *Appl. Energy*, vol. 263, no. January, p. 114599, 2020.
[21] K. de Kleijne, S. V. Hanssen, L. van Dinteren, M. A. J. Huijbregts, R. van Zelm, and H. de Coninck, "Limits to Paris compatibility of CO2 capture and utilization," *One Earth*, vol. 5, no. 2, pp. 168–185, 2022.
[22] C. Fernández-Dacosta *et al.*, "Prospective techno-economic and environmental assessment of carbon capture at a refinery and CO2 utilisation in polyol synthesis," *J. CO2 Util.*, vol. 21, no. November 2016, pp. 405–422, 2017.
[23] A. C. Hetherington, A. L. Borrion, O. G. Griffiths, and M. C. McManus, "Use of LCA as a development tool within early research: Challenges and issues across different sectors," *Int. J. Life Cycle Assess.*, vol. 19, no. 1, pp. 130–143, 2014.
[24] G. Faber *et al.*, "Adapting Technology Learning Curves for Prospective Techno-Economic and Life Cycle Assessments of Emerging Carbon Capture and Utilization Pathways," *Front. Clim.*, vol. 4, no. April, pp. 1–14, 2022.
[25] L. R. Adrianto *et al.*, "How can LCA include prospective elements to assess emerging technologies and system transitions? The 76th LCA Discussion Forum on Life Cycle Assessment, 19 November 2020," *Int. J. Life Cycle Assess.*, vol. 26, no. 8, pp. 1541–1544, 2021.
[26] F. Piccinno, R. Hischier, S. Seeger, and C. Som, "Predicting the environmental impact of a future nanocellulose production at industrial scale: Application of the life cycle assessment scale-up framework," *J. Clean. Prod.*, vol. 174, pp. 283–295, 2018.
[27] S. Gavankar, S. Suh, and A. A. Keller, "The Role of Scale and Technology Maturity in Life Cycle Assessment of Emerging Technologies: A Case Study on Carbon Nanotubes," *J. Ind. Ecol.*, vol. 19, no. 1, pp. 51–60, 2015.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***

[28] European Commission, “Technology readiness levels (TRL): extract from Part 19 - commission decision C(2014)4995,” 2014.

[29] R. Chauvy, N. Meunier, D. Thomas, and G. De Weireld, “Selecting emerging CO2 utilization products for short- to mid-term deployment,” *Appl. Energy*, vol. 236, no. December 2018, pp. 662–680, 2019.

[30] G. A. Buchner, K. J. Stepputat, A. W. Zimmermann, and R. Schomäcker, “Specifying Technology Readiness Levels for the Chemical Industry,” *Ind. Eng. Chem. Res.*, vol. 58, no. 17, pp. 6957–6969, 2019.

[31] F. Piccinno, R. Hischier, S. Seeger, and C. Som, “From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies,” *J. Clean. Prod.*, vol. 135, pp. 1085–1097, 2016.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No ***884418***