


Life Cycle & Sustainability

Methanol to polypropylene: life cycle assessment and a preliminary social impact analysis

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Abstract

Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA) are currently essential tools for evaluating the sustainability of products and industrial systems. Although LCA is systematically applied today and is considered a stable methodology, supported by material-specific guidelines and rich databases, S-LCA remains immature in certain aspects. In the presented case study, LCA was applied to compare 11 methanol synthesis processes, all based on reverse Water-Gas Shift, but characterized by different sources of CO₂ and H₂ supply, to identify the most promising. Accordingly, the model was then integrated with that of propylene production (methanol to propylene—MtP), identified as a molecule of interest for the current and future market. Then, the authors propose an innovative approach to enhance the application of S-LCA in the industrial chemistry sector. The climate change impact of the different methanol production scenarios varies significantly: the most impactful is the methanol synthesis via coal gasification (2.76 kg CO₂ eq), and the most promising are via CO₂ generated by wood chips waste or dedicated biomass by employing hydrogen produced with wind electrolysis, which show the negative impacts of −0.40 kg CO₂ eq thanks to cogeneration and the use of hydrogen from renewable sources. On the social level, the database shows a preference for productions occurring in Europe, across all the categories analyzed. The proposal of a sector-specific guideline represents a step forward that could facilitate the future application of the methodology. Moreover, the integration of LCA and S-LCA proves effective in delivering a richer and more comprehensive understanding of the issues addressed, offering valuable insights for stakeholders. The LCA should be applied to assess the environmental sustainability of alternative production routes in chemical processes, while the complexity of S-LCA can be mitigated by initiating preliminary assessments.

Keywords: life cycle assessment, social life cycle assessment, methanol to propylene

Introduction

Methanol and propylene industrial production

Methanol, also known as methyl alcohol (CH₂OH or MeOH), is the simplest of the aliphatic alcohols and is a chemical of crucial industrial interest. Its global production has been steadily increasing, from 21 million tons per year in 1989 to 110 million tons currently produced in more than 90 facilities (Methanol Institute, 2022). Historically, methanol was obtained through the rectification of wood spirit (Fiedler et al., 2000). However, modern industrial production relies on advanced catalytic processes employing compounds such as zinc oxide and chromium oxide (Stiles, 1977). Although MeOH is used primarily as a solvent (85% of the total production), it also serves as a key feedstock in various chemical industries, such as formaldehyde (Waters et al., 2003), dimethyl ether (Bakhtyari & Rahimpour, 2018), and for the production of olefins (J. Liu et al., 2009). In addition to its chemical applications, methanol is also exploitable in the energy sector, possessing suitable characteristics to be used as a fuel for racing and marine vehicles and offering cleaner combustion compared to gasoline and diesel, with lower emissions of NO_x

and particulate matter (World Economic Forum, 2023). Methanol industrial production is a well-established process that involves the generation of synthesis gas (syngas) through steam reforming of natural gas or gasification of coal and biomass. Syngas can be finally converted to methanol in the ranges of temperature 250–300 °C and pressure 5–10 MPa, using CuO/ZnO/Al₂O₃ catalyst (Jadhav et al., 2014).

However, in recent years, innovative production routes have been explored to reduce the environmental impact of CH₃OH synthesis by relying on alternative sources that do not derive from fossil materials. One promising approach is the hydrogenation of CO₂, a process that has gained significant attention also due to its potential to reduce its amount in the atmosphere (Ali et al., 2015). The conversion of CO₂ into methanol can be obtained via reverse Water-Gas Shift (rWGS), reducing CO₂ to CO in the presence of H₂ through intermediate species such as COOH· and HCO· radicals. Catalysts like Cu or Pt facilitate this process, whereas dopants enhance selectivity and efficiency for subsequent methanol synthesis (Azhari et al., 2022). Before entering in the rWGS reactor, CO₂ must be separated from outflow gases by the installation of dedicated membranes or by collection

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via carbon capture and utilization (CCU) technologies, with the latter representing an attractive strategy to convert low-cost feedstock into high-value products while reducing costs, energy consumption, and dependence on fossil carbon, reducing at the same time its atmospheric concentrations (Coralli et al., 2023). Concerning the available CO₂ sources, Yu et al. (2025) highlight the potential of integrating mature biomass-fired generation into renewable methanol synthesis routes, showing that flexible and coordinated planning of energy and carbon sources can significantly reduce production costs while enhancing carbon utilization efficiency. Qaderi (2020) conducted a comprehensive review of the reaction mechanisms involved in CO₂ hydrogenation for methanol synthesis, highlighting the significance of catalytic CO₂ reduction as a strategy to lower greenhouse gas concentrations and promote renewable energy production. Similarly, recent research has explored the integration of electrochemical and thermochemical routes to enhance methanol synthesis efficiency and reduce environmental burdens. Similarly, the source of hydrogen employed in the synthesis could determine the final impact values of the developed systems (Puig-Samper et al., 2024). In particular, hydrogen can be drawn from more traditional sources such as methane (steam reforming), coal (gasification), petroleum refinery, electrolysis, or syngas (after separation; Cetinkaya et al., 2012). A recent study (Jog et al., 2025) emphasized the potential of combining renewable hydrogen sources with CO₂-derived methanol production, and Huang et al. (2025) provided an environmental assessment on green hydrogen production via solar-powered water electrolysis, underscoring the importance of selecting renewable configurations (e.g., standalone photovoltaic) to minimize climate and resource impacts. Among the various applications of methanol, the production of propylene (MtP) is considered of notable interest, having been developed to meet the growing market demand for this compound. Propylene is the precursor of polypropylene, a versatile polymer that plays a role in several sectors, among which is the packaging industry (Arfelli et al., 2024). The high versatility of polypropylene is demonstrated by its evolving market share, which increased from \$94.5 billion in 2015 to \$130.5 billion in 2024 (+38%; Statista Research Department, 2025).

Sustainability assessment approaches

In order to demonstrate the environmental advantages associated with the proposed strategies, a standardized assessment by means of Life Cycle Assessment (LCA) should be carried out. According to the definition proposed by ISO 14040-14044, LCA is a strategic technique to identify and quantify the potential environmental impacts associated with a product, process, or system throughout its life cycle (International Organization for Standardization, 2006a, 2006b). In addition to LCA, to provide a more exhaustive sustainability evaluation, the recent publication of the Safe and Sustainable by Design (SSbD) framework includes the application of the Social Life Cycle Assessment (S-LCA) within the fifth voluntary stage, intended as a complementary approach capable of evaluating the social impacts along the entire supply chain. Social Life Cycle Assessment has recently been standardized with ISO 14075:2024 (International Organization for Standardization, 2024), responding to the increasing interest of the scientific community in social impact assessment. Although a growing number of S-LCA applications exist, the literature still recognizes that further development is required (Van Dulmen et al., 2025).

Currently, although some advancements have been made in the development of sector-specific approaches for S-LCA—such as the framework proposed by the World Business Council for

Sustainable Development (WBCSD, 2016) for evaluating social metrics in chemical products—there are still notable limitations. In particular, the availability of detailed and widely accepted guidelines tailored to certain complex sectors (e.g., the chemical industry) remains limited. In contrast, the environmental LCA benefits from more established standardization instruments, such as Product Category Rules (PCRs), which support consistency in data management and impact assessment. Recent developments like the publication of Social Product Declarations (SPDs), including the SPD-PCR 2023:01 for Rolling Stock (Hitachi Rail STS SpA, 2023), represent a promising step toward formalizing S-LCA practices. However, these efforts are still emerging and have yet to reach comprehensive applicability across all industrial sectors. Among others, one of the most important criticalities of S-LCA is embodied in the need to quantitatively relate the existing indicators to the functional unit (FU) of the system (Settembre Blundo et al., 2014). Therefore, further research is needed to refine and consolidate S-LCA methodologies, particularly to ensure their relevance, robustness, and usability in sectors like the chemical industry, which continues to lack a widely recognized framework. Beyond this, the lack of primary data is certainly one of the main obstacles to conducting S-LCA analyses (M. Liu et al., 2024). However, although this absence represents a significant limitation, it does not preclude the possibility of performing screening analyses that provide a preliminary understanding of the context and, ideally, encourage more comprehensive S-LCA studies in the future.

The authors found the existence of a relevant and increasing interest in the production of the molecules investigated in the presented article. For instance, Liu et al. (2024) proposed an LCA analysis on various typical methanol production methods with a particular focus on methanol synthesis via coal gasification (CtM), biomass gasification (BtM), steam reforming of natural gas (NGtM), and CO₂ capture to methanol route (CO₂tM). Among the alternatives, CtM was identified as the worst option concerning both ecosystems and human health-related impacts. Chen et al. (2019) provided a similar comparison, obtaining the same results. In particular, they demonstrated that CtM option results are competitive with the other options only by reducing the fossil fraction of the electricity mix. Güleröglü and Yumurtacı (2025) applied LCA to assess green methanol production based on hybrid solar-wind systems with seasonal energy storage. They found that this configuration can reduce global warming potential by 24%–28% compared to a grid-based system. Emphasizing the attention on the topic proposed in this study, Rigamonti and Brivio (2022) and Rafiq et al. (2024) applied LCA to product systems designed to produce methanol from CO₂. The former, which involved the use of CO₂ derived from CCU, showed that the specific synthesis route did not significantly influence the overall impacts. Rather, the main benefits were associated with the avoided emissions of CO₂ into the atmosphere. The latter obtained similar results, emphasizing the positive influence that would have the employment of renewable electricity and also estimating an economic advantage.

Despite LCA studies related to methanol and propylene being widely available in the recent literature, no S-LCAs have been applied to the two molecules yet. According to the demonstrated interest, the presented study applies LCA to different MeOH production pathways and to their conversion to propylene, with a focus on exploring S-LCA. The goal is to provide a comparison between established and innovative options to produce methanol and to estimate their contribution in the final synthesis of propylene. Then, a preliminary S-LCA is applied to the MtP synthesis

to propose a guideline that can facilitate the development of future S-LCA studies in the field of industrial chemistry, addressing a gap in the existing literature.

Methods

Life Cycle Assessment and Social Life Cycle Assessment are standardized methodologies, respectively, ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization, 2006a, 2006b), and ISO 14075:2024 (International Organization for Standardization, 2024). Both are structured on four interconnected phases: (1) Goal and scope definition, (2) Life Cycle Inventory (LCI and S-LCI); (3) Life Cycle Impact Assessment (LCIA and S-LCIA), and (4) Interpretation. Whereas LCA addresses the potential environmental impacts/benefits, S-LCA is focused on social and socioeconomic aspects (both positive and negative). The paragraphs below detail each stage by maintaining a separate discussion.

Life cycle assessment

Goal and scope definition

This study consists of the application of LCA to 11 methanol synthesis pathways, namely NGtM, CtM, BMtM, and eight variations of CO₂tM and the MtP reaction, considering all the different methanol-production strategies. It follows a cradle-to-gate approach, including in the evaluation: extraction, manufacturing, and supply of raw materials and intermediates involved in the production; generation, supply, and consumption of the energy carriers (e.g., electricity from the grid); and operative phases. The packaging stage, distribution, usage, and end-of-life management of propylene (downstream) are excluded from the analysis because they are out of the scope. A detailed system boundary is depicted in Figure 1.

The study is structured on two different levels of analysis. The first (Level I) focuses on the methanol production and was used to study in detail the different production scenarios. At this level, the FU was set at 1 kg of methanol. During Level II, the system is extended to consider the employment of methanol in an MtP process performed within the same plant and by incorporating the previously defined scenarios in the propylene synthesis. The FU of Level II is then switched to 1 kg of propylene. China was selected to meet the geographical correlation requested by the ISO, since it represents the major producer worldwide. The aims of the proposed work can be summarized as follows: (1) to calculate and compare the environmental impacts associated with different scenarios for methanol production; (2) to assess the environmental impacts related to the MtP synthesis, according to the scenarios previously modeled; (3) to provide a preliminary S-LCA evaluation on MtP synthesis; and (4) to propose a guideline to facilitate the development of future S-LCA studies in the field of the industrial chemistry sector. Data collection and model assumptions for the scenarios investigated are described below. For background information and secondary data, the reference database was ecoinvent 3.10 (Wernet et al., 2016) with the default processes set to At Point of Substitution (APOS) allocation and Unit Process (U). The model was generated on the software OpenLCA (version 2.3; GreenDelta, 2024). A detailed description of the scenarios is reported in the LCI section.

Life cycle inventory

(1) CO₂ to methanol routes (Level I)

The production of methanol via CO₂ hydrogenation (Figure 1) consists of a series of processes involving: (1) biomass combustion, (2) CO₂ separation from the exhaust gas stream, (3) reverse Water-Gas Shift reaction (rWGS), and (4) methanol synthesis. In Figure 1, the first two stages are grouped into a single cogeneration process (red boundaries). Biomass combustion produces

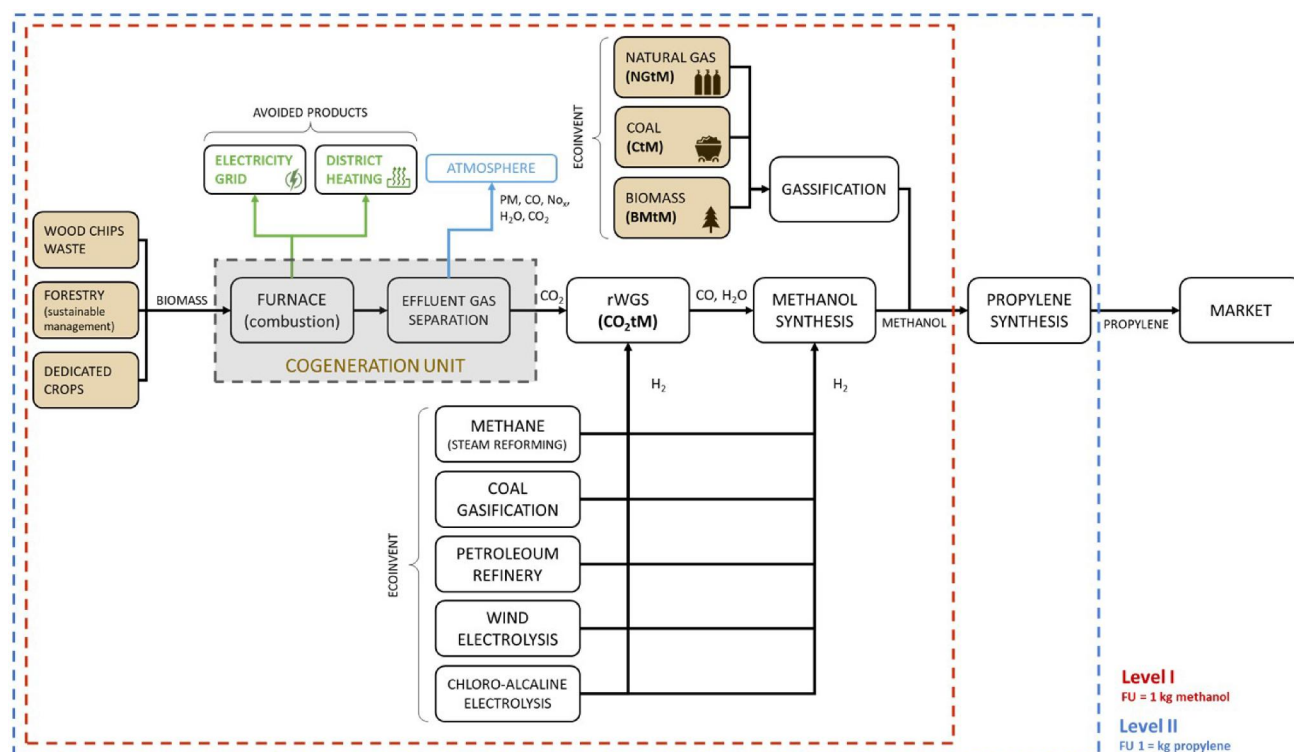


Figure 1. Representation of the system boundaries and all the processes involved in the different methanol and propylene production alternatives. Red dashed lines refer to Level I, whereas blue dashed lines refer to Level II. Ocher-colored boxes represent the different carbon sources.

biogenic CO₂ (b-CO₂), which represents about 99% of the total air emissions according to the ecoinvent database, energy and heat flows, and emissions such as unburned particulate material, CO, NO_x, water vapor, etc.

Since b-CO₂ serves as one of the primary inputs for the subsequent rWGS process, the proposed LCA model considers b-CO₂ generated as the desired product (target), with energy and heat as co-products, credited as “avoided products.” Further details about the choice are reported in the “Methodological Choices” section of the [online supplementary material](#). As anticipated in the introduction, the separation of CO₂ from the impure gas effluent requires either the use of membranes or CCU. However, the literature lacks representative and comprehensive data to account for the material and energy flows associated with this phase in the LCA model, and, accordingly, the authors propose a conservative yet arbitrary separation efficiency of 95%. Deeper details about the choice are reported in the “Methodological Choices” section of the [online supplementary material](#). Once purified, the CO₂ undergoes the rWGS reaction, followed by the methanol synthesis reaction. The eight explored scenarios, combining various sources of CO₂ and H₂, are summarized in [Table 1](#) and depicted in [Figures S2–S9](#) and [Tables S1–S8](#) of the [online supplementary material](#), respectively, CO₂tM-dedicated biomass CO₂ methane H₂ (CO₂tM-dbCO₂mH₂), CO₂tM-dedicated biomass CO₂ coal H₂ (CO₂tM-dbCO₂cH₂), CO₂tM-dedicated biomass CO₂ petroleum H₂ (CO₂tM-dbCO₂pH₂), CO₂tM-dedicated biomass CO₂ electrolysis H₂ (CO₂tM-dbCO₂eH₂), CO₂tM-dedicated biomass CO₂ wind electrolysis H₂ (CO₂tM-dbCO₂weH₂), CO₂tM-wood chips waste CO₂ methane H₂ (CO₂tM-wcw0CO₂mH₂), CO₂tM-sustainable management CO₂ methane H₂ (CO₂tM-smCO₂mH₂), and CO₂tM- wood chips waste CO₂ wind electrolysis H₂ (CO₂tM-wcw0CO₂weH₂).

(2) Natural gas/coal/biomass to methanol routes (Level I)

The NGtM, CtM, and BMtM routes have been extensively investigated in the scientific literature. [Chen et al. \(2019\)](#), [J. Liu et al. \(2024\)](#), and [Y. Liu et al. \(2020\)](#) have been selected as references to draw the inventory data needed to generate the models in the software. For the CO₂tM technological route under investigation, comprehensive process-level input and output data were systematically collected and are reported in [Table 2](#). The data were collected using the reaction schemes described by [Cavani et al. \(2022\)](#). The product systems representing the processes involved in the three scenarios are depicted in [Figures S10–S12](#) and [Tables S9–S11](#) of the [online supplementary material](#).

The remaining pathways (NGtM, CtM, BMtM) were simulated using specific ecoinvent proxies and by considering the FUs for Level I and Level II (respectively, methanol production, natural gas reforming | methanol | APOS, U—CN; methanol production, coal gasification | methanol | APOS, U—CN; methanol production, biomass gasification | methanol, from biomass | APOS, U—CH). The biomass gasification process (the latter one) specific to China

is not available in the ecoinvent database, and “CH” has been selected as the representative version. More details about the consistency of the choice are reported in the “Methodological Choices” section of the [online supplementary material](#).

(3) Methanol to propylene route (Level II)

Methanol to propylene is widely used in China, where the first commercial-scale application has been developed ([Haag et al., 2012](#)). The selected production technology is the “Lurgi’s MtP process,” which represents the most efficient scheme for producing propylene and for retaining a low coking tendency, while maintaining a very low propane and by-products yield ([Wernet et al., 2016](#)). Data related to this process, which is assumed to be performed in proximity to methanol synthesis, to avoid transportation burdens, were obtained from the ecoinvent database “propylene production, from methanol-to-propylene conversion | propylene | APOS, U-CN,” by adjusting the MeOH supply chain accordingly to the previously created scenarios. The flowsheet of Lurgi’s MtP synthesis is provided in [Figure S1](#) of the [online supplementary material](#). In the first stage of the Lurgi MtP process, methanol is dehydrated to form dimethyl ether and water. In the second stage, dimethyl ether is converted into a mixture of light olefins through catalytic reactions. A proprietary zeolite-based catalyst is used to maximize propylene selectivity over ethylene and other by-products ([Koempel & Liebner, 2007](#)).

Life cycle impact assessment

IPCC 2021 (version 1.02; [Intergovernmental Panel On Climate Change, 2023](#)) and ReCiPe 2016 (version 1.03; [Huijbregts et al., 2017](#)) were selected as reference analysis methods, to investigate 18 midpoint impact categories: CC, climate change (kg CO₂ eq), OD, stratospheric ozone depletion (kg CFC11 eq); IR, ionizing radiation (kBq Co-60 eq); HOF, ozone formation-human health (kg NO_x eq); PMF, fine particulate matter formation (kg PM 2.5 eq); EOF, ozone formation terrestrial ecosystems (kg NO_x eq); TA, terrestrial acidification (kg SO₂ eq); FE, freshwater eutrophic (kg P eq); ME, marine eutrophic (kg N eq); TET, terrestrial ecotoxicity (kg 1,4-DCB eq); FET, freshwater ecotoxicity (kg 1,4-DCB eq); MET, marine ecotoxicity (kg 1,4-DCB eq); HTC, human carcinogenic toxicity (kg 1,4-DCB eq); HTnc, human noncarcinogenic toxicity (kg 1,4-DCB eq); LO, land occupation (m²a crop eq); MRD, mineral resource scarcity (kg Cu eq); FD, fossil resource scarcity (kg oil eq); WC, water consumption (m³). Climate change (CC) was addressed through IPCC 2021 (GWP100), category selected to run a hotspot analysis for all the CO₂tM created scenarios.

Sensitivity and uncertainty analysis

The outcomes of the contribution analysis were taken as the reference for setting the sensitivity analysis, performed to test the robustness of the model created and to enable identification and quantification of the influence of the main exogenous parameters on the environmental impact of the entire system ([Wei et al.,](#)

Table 1. CO₂ to methanol (CO₂tM) scenarios.

Process	Acronym	CO ₂ source	H ₂ source
CO ₂ tM-dedicated biomass CO ₂ methane H ₂	CO ₂ tM-dbCO ₂ mH ₂	Wood chips from dedicated crops	Methane steam reforming
CO ₂ tM-dedicated biomass CO ₂ coal H ₂	CO ₂ tM-dbCO ₂ cH ₂	Wood chips from dedicated crops	Coal gasification
CO ₂ tM-dedicated biomass CO ₂ petroleum H ₂	CO ₂ tM-dbCO ₂ pH ₂	Wood chips from dedicated crops	Petroleum refinery, low pressure H ₂
CO ₂ tM-dedicated biomass CO ₂ electrolysis H ₂	CO ₂ tM-dbCO ₂ eH ₂	Wood chips from dedicated crops	Chloro-alkaline electrolysis
CO ₂ tM-dedicated biomass CO ₂ wind electrolysis H ₂	CO ₂ tM-dbCO ₂ weH ₂	Wood chips from dedicated crops	Wind electrolysis
CO ₂ tM-wood chips waste CO ₂ methane H ₂	CO ₂ tM-wcw0CO ₂ mH ₂	Wood chips waste (0 impact)	Methane steam reforming
CO ₂ tM-sustainable management CO ₂ methane H ₂	CO ₂ tM-smCO ₂ mH ₂	Sustainable forest management	Methane steam reforming
CO ₂ tM-wood chips waste CO ₂ wind electrolysis H ₂	CO ₂ tM-wcw0CO ₂ weH ₂	Wood chips waste (0 impact)	Wind electrolysis

Table 2. CO₂ to methanol (CO₂tM) life cycle inventory.

Inputs	Amount	Unit	Output	Amount	Unit
Biomass combustion					
Biomass	0.10	kg	CO ₂	1.37	kg
			Energy	0.68	kWh
			Heat	0.93	kWh
Reverse Water-Gas Shift (rWGS)					
CO ₂	1.37	kg	CO	0.87	mol
r-H ₂	0.063	kg	H ₂ O	0.56	kg
MeOH synthesis					
CO	0.87		MeOH	1	kg
r-H ₂	0.13				

2015). The many scenarios analyzed in the case study provide an exhaustive assessment of the influence of various design choices for the product system. However, beyond the different configurations involving the use of various sources of carbon and hydrogen, the authors chose to investigate the influence of assuming a CO₂ separation efficiency of 95% in the effluent gas separation (EGS) process. Specifically, in the sensitivity analysis, the efficiency of the scenario CO₂tM-dedicated biomass CO₂ methane H₂ was first reduced to 70% and then increased to 100%, assuming the unseparated CO₂ would be emitted into the atmosphere.

Uncertainty evaluation and propagation were performed both for midpoint categories by employing the pedigree data quality matrix (Weidema & Wesnæs, 1996). A Monte Carlo simulation with 10,000 runs was also conducted to investigate how the intrinsic variability of the parameters and the quality of the data used in the modeling may impact the outcomes. The scores selected for compiling the pedigree matrix are reported in Table S13 of the online supplementary material. Data related to the product systems analyzed derived from secondary information and data quality criteria, regarding, for instance, geographical, temporal, and technological representativeness, have been accordingly defined.

S-LCA

As anticipated above, the main objective is to conduct a preliminary S-LCA to the MtP synthesis, with the aim of supporting the development of a guideline applicable to industrial chemistry. The selected FU is the same as in Level II of the LCA study: 1 kg of propylene produced in China, ready to be introduced in the market (packaging excluded). Ideally, an S-LCI should be based on primary data collected specifically for each production site—for instance, through direct surveys prepared ad hoc for the context of analysis (United Nations, 2020). However, in the absence of foreground data, databases or scientific literature can be used as secondary sources, although they provide less context-specific information. In particular, tools such as the Risk Mapping Tool (SHDB, s.d.) can be employed to identify potential social risks associated with specific sectors or countries, thereby supporting the selection of key aspects for further investigation. Due to the lack of direct contact with propylene-producing companies (primarily located in China), the presented study relied on database information regarding the social context of the Chinese chemicals, rubber, and plastics sector, using the Risk Mapping Tool as a screening tool.

Italy and Germany were selected as benchmark countries due to their historical and international relevance in the industrial chemistry sector (Lesch, 2000; Papeo & Pulici, 2013), assuming them to be representative of the European context. Conversely, China was selected based on the geographic localization of propylene production processes in the ecoinvent database, which

reflects a significant share of production originating from this country. Because S-LCA is highly dependent, first, on site-specific conditions and, second, on national regulations and contexts, we decided to base the screening analysis on these three countries to provide a comparative perspective as well as a preliminary indication of “national hotspots” to be evaluated in the case of a full assessment. Moreover, this preliminary analysis will support the proposal of sector-specific guidelines for the chemical industry (see the section “Proposed Guidelines for the Chemical Sector”).

Results and discussion

Life cycle assessment results

Level I results

Climate change was chosen as an environmental indicator to screen the MeOH production scenarios (NGtM, CtM, BMtM, and CO₂tM). Figure 2 collects the net carbon footprint results calculated based on IPCC 2021 method. Because carbon footprint reflects the potential impacts on CC, it was selected as a cutoff criterion to proceed with the analysis of the whole set of environmental impacts. In order to be considered suitable for an in-depth analysis, the CO₂-based routes should demonstrate competitiveness in terms of overall carbon intensity.

As shown, the CtM scenario exhibits the highest CC impact (2.76 kg CO₂eq), highlighting the relevance of coal combustion (54.2%), followed by coal and oxygen production and supply (16.9% and 28.9%, respectively). A similar situation emerged for the CO₂tM-wcCO₂CH₂ scenario, which ranks second in CC impact (1.86 kg CO₂eq). The NGtM and BMtM scenarios exhibit lower impacts, with values ranging from 0.52 to 0.13 kg CO₂eq, respectively. These results are comparable to some of the CO₂tM, which, as previously noted, display environmental impact variations on CC depending on the CO₂ and hydrogen sources employed. Notably, the CO₂tM-dbCO₂weH₂ and CO₂tM-wcwCO₂weH₂ scenarios achieve the most favorable results, with a net negative impact of −0.40 kg CO₂eq, due to the contribution of direct impacts and credit assigned to the energy recovered in cogeneration. Finally, the CO₂tM-wcCO₂pH₂ scenario also exhibits a negative impact, albeit lower in magnitude (−0.21 kg CO₂eq). The complete contribution analysis is reported in Table S14 of the online supplementary material.

An uncertainty analysis was also conducted using the Monte Carlo method to evaluate how data quality influences the reliability of the estimated environmental impacts. For processes already modeled within ecoinvent (CtM, BMtM, NGtM), the intrinsic uncertainties of the respective datasets were retained. Consequently, the high standard deviation associated with the CtM process is due to database proxies rather than modeling choices, which highlights the importance of working with primary data when available (Barahmand & Eikeland, 2022). For the CO₂tM scenario, data quality was assessed using the pedigree matrix. The uncertainty analysis indicates that it is not possible to identify the best methanol production strategy among those investigated definitively. However, some scenarios, such as CO₂tM-dbCO₂weH₂ and CO₂tM-wcwCO₂weH₂, appear to be preferable to others. The tables containing standard deviations for each analysis are provided in the online supplementary material (see Table S15).

The results of the contribution analysis performed for the CO₂tM scenarios are also reported in Figure 3 and online supplementary Table S14. They indicate that in all scenarios, the cogeneration phase contributes negatively to the impact (i.e., positively

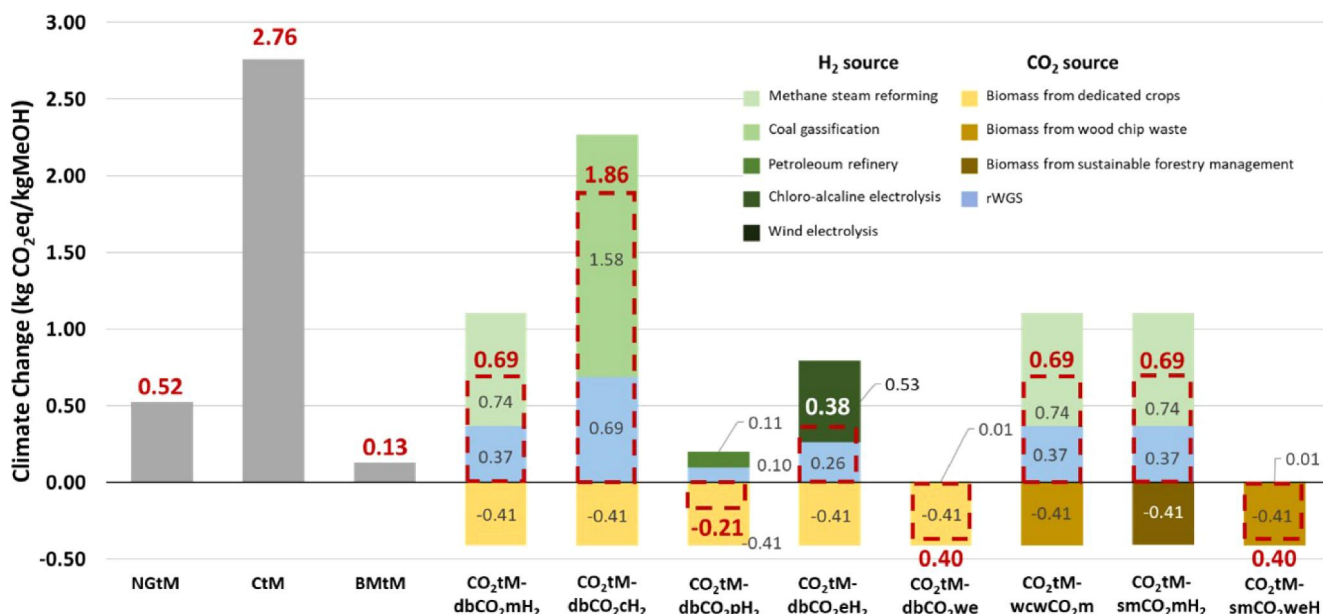


Figure 2. Contribution analysis of NGtM (natural gas to methanol), CtM (carbon to methanol), BMtM (biomass to methanol), and the investigated scenarios of the CO₂tM (CO₂ to methanol) reaction in terms of kg CO₂eq, Level I. Dashed columns represent the net environmental impact. CO₂tM-dedicated biomass CO₂ methane H₂ (CO₂tM-dbCO₂mH₂), CO₂tM-dedicated biomass CO₂ coal H₂ (CO₂tM-dbCO₂cH₂), CO₂tM-dedicated biomass CO₂ petroleum H₂ (CO₂tM-dbCO₂pH₂), CO₂tM-dedicated biomass CO₂ electrolysis H₂ (CO₂tM-dbCO₂eH₂), CO₂tM-dedicated biomass CO₂ wind electrolysis H₂ (CO₂tM-dbCO₂weH₂), CO₂tM-wood chips waste CO₂ methane H₂ (CO₂tM-wcw0CO₂mH₂), CO₂tM-sustainable management CO₂ methane H₂ (CO₂tM-smCO₂mH₂), and CO₂tM- wood chips waste CO₂ wind electrolysis H₂ (CO₂tM-wcw0CO₂weH₂).

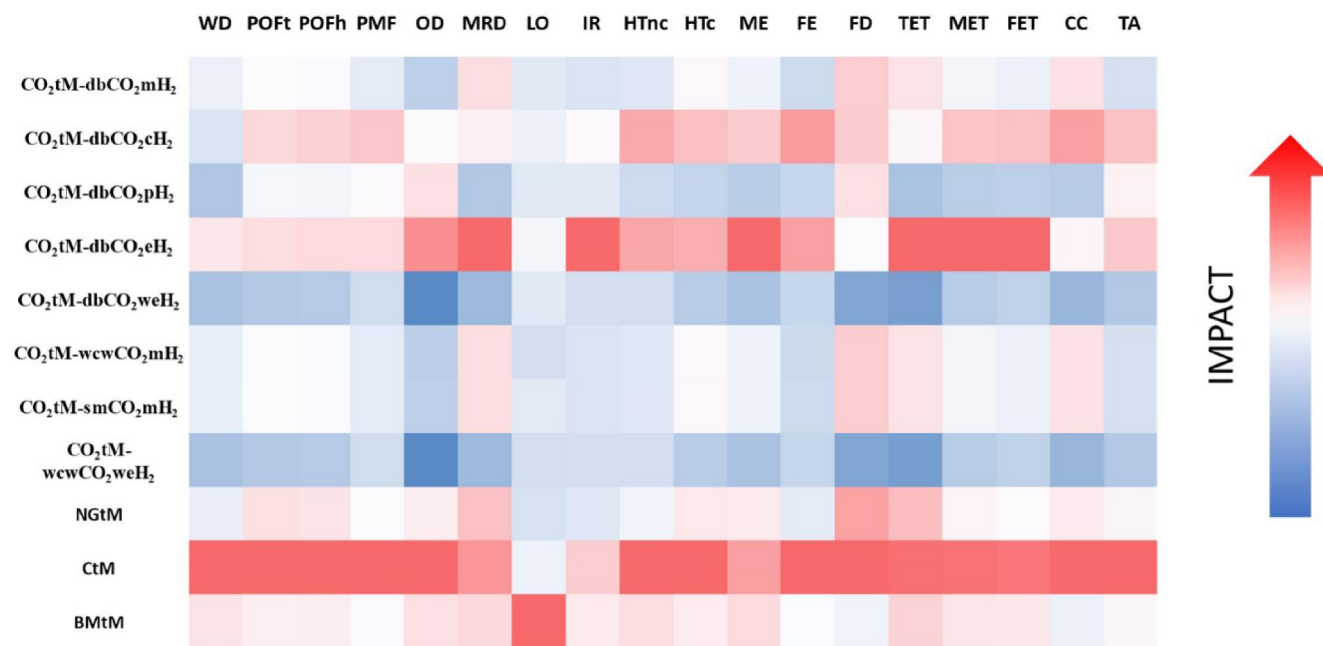


Figure 3. Contribution analysis by impact category at the midpoint level of the ReCiPe 2016 method, Level I. CC = climate change (kg CO₂ eq), OD = stratospheric ozone depletion (kg CFC11 eq); IR = ionizing radiation (kBq Co-60 eq); HOF = ozone formation-human health (kg NO_x eq); PMF = fine particulate matter formation (kg PM 2.5 eq); EOF = ozone formation terrestrial ecosystems (kg NO_x eq); TA = terrestrial acidification (kg SO₂ eq); FE = freshwater eutrophication (kg P eq); ME = marine eutrophication (kg N eq); TET = terrestrial ecotoxicity (kg 1,4-DCB eq); FET = freshwater ecotoxicity (kg 1,4-DCB eq); MET = marine ecotoxicity (kg 1,4-DCB eq); HTc = human carcinogenic toxicity (kg 1,4-DCB eq); HTnc = human noncarcinogenic toxicity (kg 1,4-DCB eq); LO = land occupation (m²a crop eq); MRD = mineral resource scarcity (kg Cu eq); FD = fossil resource scarcity (kg oil eq); WC = water consumption (m³). CO₂tM-dedicated biomass CO₂ methane H₂ (CO₂tM-dbCO₂mH₂), CO₂tM-dedicated biomass CO₂ coal H₂ (CO₂tM-dbCO₂cH₂), CO₂tM-dedicated biomass CO₂ petroleum H₂ (CO₂tM-dbCO₂pH₂), CO₂tM-dedicated biomass CO₂ electrolysis H₂ (CO₂tM-dbCO₂eH₂), CO₂tM-dedicated biomass CO₂ wind electrolysis H₂ (CO₂tM-dbCO₂weH₂), CO₂tM- wood chips waste CO₂ methane H₂ (CO₂tM-wcw0CO₂mH₂), CO₂tM-sustainable management CO₂ methane H₂ (CO₂tM-smCO₂mH₂), and CO₂tM-wood chips waste CO₂ wind electrolysis H₂ (CO₂tM-wcw0CO₂weH₂).

for the environment), with values ranging between -0.409 kg CO₂eq and -0.411 kg CO₂eq. This is due to credits of reactant (CO₂) and energy co-generation, both of which are well-

recognized strategies for reducing the overall emissions of industrial systems (Lombardi et al., 2018). The impacts of the rWGS reaction exhibit significant variability, driven by the different

sources of reagents used. In the CO₂tM-wcCO₂cH₂ scenario, which relies on hydrogen derived from coal gasification, the rWGS reaction presents the highest contribution (0.69 kg CO₂eq). Conversely, in the CO₂tM-dbCO₂weH₂ and CO₂tM-wcwCO₂weH₂ scenarios, where green hydrogen is employed, the impact of the rWGS reaction is negligible (2.82E-3 kg CO₂eq).

Hydrogen production emerges as particularly relevant, contributing 1.58 kgCO₂eq in the CO₂tM-dbCO₂cH₂ scenario (mainly because of coal combustion) and only 5.56E-3 kg CO₂eq in the CO₂tM-dbCO₂weH₂ and CO₂tM-wcwCO₂weH₂ scenarios, which exhibit minimal hydrogen-related impacts thanks to the wind-powered electricity used for electrolysis. An interesting finding is observed in the CO₂tM-dbCO₂pH₂ scenario, which shows a relatively low impact (0.21 kg CO₂eq) associated with H₂ production. This result is partially justified by the inferior estimated impact of petroleum sourcing, which is significantly lower (−81%) compared to coal (as seen in the CO₂tM-wcCO₂cH₂ scenario). Among the various processes and flows considered, the most significant differences in terms of both quantity and contribution are related to the input of petroleum and coal, respectively, as well as the amount of CO₂ released into the atmosphere during the conversion. Given that the amount of hydrogen produced remains the same in both cases (i.e., 9.16E-2 kgH₂), the input of petroleum amounts to 2.78E-1 kg, whereas coal reaches 5.66E-1 kg. These inputs result in emissions of 0.06 kg CO₂ eq and 0.32 kg CO₂ eq, respectively. Furthermore, the amount of CO₂ directly emitted into the atmosphere is 0.08 kg in the case of petroleum, compared to 1.48 kg for coal. These represent the main differences between the two processes and support the preferability of the petroleum-based route with respect to the CC impact category.

Figure 3 depicts the results of the hotspot analysis of each life cycle stage by extending the perspective to the other 17 midpoint categories (numerical results are reported in [online supplementary Table S16](#)). The analysis reveals that the CtM scenario is the most impactful choice across the majority of impact categories, with the exception of FET, MET, TET, ME, IR, LO, and MRD. After this, FET, MET, TET, IR, and MRD categories, in the CO₂tM-wcCO₂eH₂ scenario, are mainly influenced by the use of sodium chloride (in a range of 67% to 82%) in the chlor-alkali electrolysis process for hydrogen generation. Similarly, the CO₂tM-dbCO₂cH₂ impacts observed for the categories FET, HTnc, and HTC are derived mainly from the utilization of hydrogen (from 62% to 81%), produced from coal. The BMTM scenario ranks in an intermediate position, except for the land occupation (LO) category, where impacts are particularly high (+80% compared to the other scenarios) due to the cultivation of the dedicated biomass. Among the less impactful scenarios, CO₂tM-dbCO₂weH₂ and CO₂tM-wcwCO₂weH₂ emerge as more promising options, highlighting the benefits associated with the adoption of renewable energy sources in place of fossil fuels. In general, the most favorable scenarios are also those that use waste-derived feedstocks for CO₂ production.

Level II results

In Level II, the analysis was extended to the MtP stage (Figure 4 and Table 3). The propylene synthesis effect on CC impact, excluding the cradle-to-gate impacts from MeOH synthesis, was estimated at 0.28 kg CO₂eq/FU, with almost all of it of fossil origin (99.8%). If methanol production is included in the evaluation, it dominates the impact of the whole level II system, particularly in scenarios involving coal utilization (CtM and CO₂tM-dbCO₂cH₂). Standard deviations estimated for each impact category are provided in [online supplementary Table S15](#).

Sensitivity analysis results

As anticipated in the section “Sensitivity and Uncertainty Analysis,” the sensitivity analysis was conducted on the membrane efficiency for CO₂ separation in the EGS process of the scenario CO₂tM-dedicated biomass CO₂ methane H₂, reducing it from 95% to 70%, assuming that the unseparated CO₂ would be emitted into the atmosphere, and increasing it from 95% to 100%. The new scenarios resulted in a CC impact of 0.76 kg CO₂ eq (−20.0%), which is lower than the 0.95 kg CO₂ eq estimated for the baseline scenario. The final value of 0.76 kg CO₂ eq is primarily influenced by two factors: (1) the CO₂ released during the separation phase (0.30 kg instead of 0.05), which implies an increase in impact; (2) conversely, a higher demand for CO₂ results in a greater amount of biomass entering cogeneration and, consequently, a higher amount of energy produced, which in the system appears as an avoided impact, thus a credit, falling into the paradox already highlighted by [Arfelli et al. \(2023\)](#), where avoided production of energy reflects a reduction in CC impacts. Conversely, the increasing efficiency from 95% to 100% determined a CC value of 0.97 kg CO₂ eq. (+2.1%), confirming the previous considerations.

S-LCA results

From the analysis conducted using the Risk Mapping Tool ([SHDB, s.d.](#)), several differences emerged between China and the European countries (Italy and Germany). Among these, specific areas of concern stand out, underscoring the extent of social disparities. As anticipated before, the assessment is based on average data for the chemicals, rubber, and plastics sector, and it is not specifically related only to the propylene industry. The tool enables the allocation of a relative percentage of social impacts to each country across five macro-categories: human rights, health and safety, community, governance, and society. The results are reported in [Figure 5A](#).

The graphical analysis indicates that China’s cumulative impact exceeds that of Italy by approximately 62.5% and that of Germany by around 76.3%. [Figure 5B](#) provides a percentage breakdown of the impacts for each category relative to the total for each country. In [Figure 5C](#), the number of issues that have reached a certain risk level for each category is summarized. Further specific details on the results are provided in [online supplementary Tables S17–21](#). Specifically, [Figure 5C](#) highlights that, across all considered categories and in consistency with the proposed classification, China generally exhibits lower performance compared to Italy and Germany. This finding reflects how the average labor conditions in China are apparently lower than in Italy and Germany. The categories for which a significant difference between China and Europe was highlighted (right to association, collective bargaining, and the right to strike; child labor; freedom of speech) have been investigated for a more detailed analysis.

(1) Right to association, collective bargaining, and the right to strike

Among the differences in labor rights between China and countries like Italy and Germany, the subcategory “freedom of association, collective bargaining, and the right to strike” stands out. China exhibits a high relative impact in this area, reflecting severe deficiencies in labor rights protection. The value is confirmed by the International Trade Union Confederation ([ITUC, CSI, IGB, s.d.](#)), which sets global benchmarks for these rights and ranks China among the worst-performing countries, assigning it a score of 5 (which means: no guarantee of rights), compared to 1 for Italy and Germany. In the same report, the Asia-Pacific region

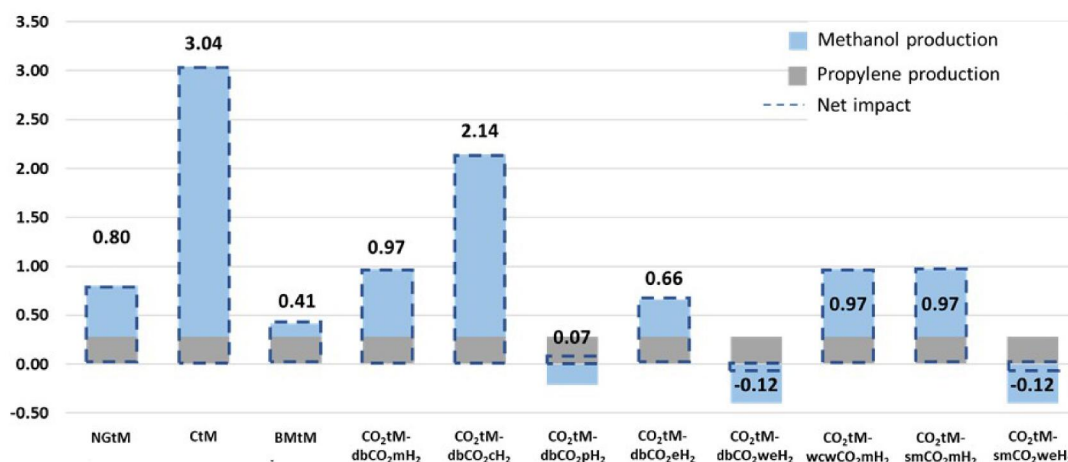


Figure 4. Climate change impact for NGtM, CtM, BMtM, and CO₂tM scenarios, Level II. CO₂tM-dedicated biomass CO₂ methane H₂ (CO₂tM-dbcO₂mH₂), CO₂tM-dedicated biomass CO₂ coal H₂ (CO₂tM-dbcO₂cH₂), CO₂tM-dedicated biomass CO₂ petroleum H₂ (CO₂tM-dbcO₂pH₂), CO₂tM-dedicated biomass CO₂ electrolysis H₂ (CO₂tM-dbcO₂eH₂), CO₂tM-dedicated biomass CO₂ wind electrolysis H₂ (CO₂tM-dbcO₂weH₂), CO₂tM-wood chips waste CO₂ methane H₂ (CO₂tM-wcwCO₂mH₂), CO₂tM-sustainable management CO₂ methane H₂ (CO₂tM-smCO₂mH₂), and CO₂tM-wood chips waste CO₂ wind electrolysis H₂ (CO₂tM-wcwCO₂weH₂).

Table 3. Impacts associated with the IPCC and ReCiPe 2016 methods for propylene synthesis.

Category	Impact result	Unit
TA	9.40E-01	kg SO ₂ eq
FET	3.47E-02	kg 1,4 DCB eq
FD	7.70E-02	kg oil eq
FET	8.80E-05	kg P eq
ME	1.56E-05	kg N eq
HTc	9.85E-02	kg 1,4 DCB eq
MET	4.73E-02	kg 1,4 DCB eq
IR	7.98E-03	kBq Co-60 eq
LO	7.09E-03	m ² *a crop eq
MRD	4.26E-03	kg Cu eq
OD	5.03E-08	kg CFC-11 eq
PMF	3.97E-04	kg PM 2.5 eq
POFh	5.04E-04	kg Nox eq
POFt	5.33E-04	kg Nox eq
WD	4.79E-03	m ³
CC	2.79E-01	kg CO ₂ eq
CC fossil	2.79E-01	kg CO ₂ eq
CC biogenic	3.50E-04	kg CO ₂ eq
CC land use	1.40E-04	kg CO ₂ eq
TET	3.96E+00	kg 1,4 DCB eq
HTnc	5.74E-01	kg 1,4 DCB eq

Note. CC = climate change (kg CO₂ eq), OD = stratospheric ozone depletion (kg CFC11 eq); IR = ionizing radiation (kBq Co-60 eq); HOF = ozone formation-human health (kg NO_x eq); PMF = fine particulate matter formation (kg PM 2.5 eq); EOF = ozone formation terrestrial ecosystems (kg NO_x eq); TA = terrestrial acidification (kg SO₂ eq); FE = freshwater eutrophic (kg P eq); ME = marine eutrophic (kg N eq); TET = terrestrial ecotoxicity (kg 1,4-DCB eq); FET = freshwater ecotoxicity (kg 1,4-DCB eq); MET = marine ecotoxicity (kg 1,4-DCB eq); HTc = human carcinogenic toxicity (kg 1,4-DCB eq); HTnc = human noncarcinogenic toxicity (kg 1,4-DCB eq); LO = land occupation (m²*a crop eq); MRD = mineral resource scarcity (kg Cu eq); FD = fossil resource scarcity (kg oil eq); WC = water consumption (m³).

is recognized to be the second worst performing at the global level, after the Middle East and North Africa. Despite formally recognizing freedom of association, China restricts it through the All-China Federation of Trade Unions (ACFTU), the only legally recognized entity. Independent unions are not allowed, and collective bargaining remains unregulated, limiting free negotiations. The right to strike was abolished in 1982 and, although not explicitly illegal today, is repressed through public security laws, with severe consequences for participants. Data from the China Labour Bulletin (China Labour Bulletin, 2024) show that

between 2011 and 2024, only six strikes were recorded in the chemical sector, all occurring in the last year. This underscores how the right to strike remains uncommon despite occasional protests.

(2) Child labor

The C138 Convention of the International Labour Organization (International Labour Organization, 1973) sets 15 years as the minimum working age, ensuring minors attend school and are protected from hazardous work. It also establishes 18 years as the minimum age for dangerous jobs. Despite these regulations, China faces a “high” risk of child labor, whereas Italy and Germany show a “low” risk. A study published in the China Economic Review (Tang et al., 2018) using 2010 China Family Panel Study data found that around 8% of children aged 10–15 were engaged in labor, mainly in rural, low-income families, reducing their study time and increasing dropout rates. The issue of child labor is more frequent in underdeveloped regions and agricultural households, whereas adult workforce availability decreases its incidence. Although sector-specific data are limited, Federchimica (Federchimica, Confindustria, 2017) reports that China holds 43% of the global chemical market, suggesting that a fraction of child laborers might be involved in this industry also.

(3) Freedom of speech

China’s governance model and its approach to freedom of expression differ in certain respects from the standards set out in European directives, a distinction that is also reflected in its classification as a high social risk within the Risk Mapping Tool. Although China is formally established as a republic, its political system is organized around the leadership of the Communist Party of China, operating within a single-party framework. Although international human rights frameworks—such as the Universal Declaration of Human Rights (Universal Declaration of Human Rights, 1948, Articolo 19, s.d.)—underscore the importance of freedom of expression, China regulates this right in accordance with its domestic priorities, which include considerations of national security, public order, and moral standards. In this context, there is a high degree of government involvement in areas such as media regulation, online communication, and civil society activities. Reports by Freedom House (2024) rank

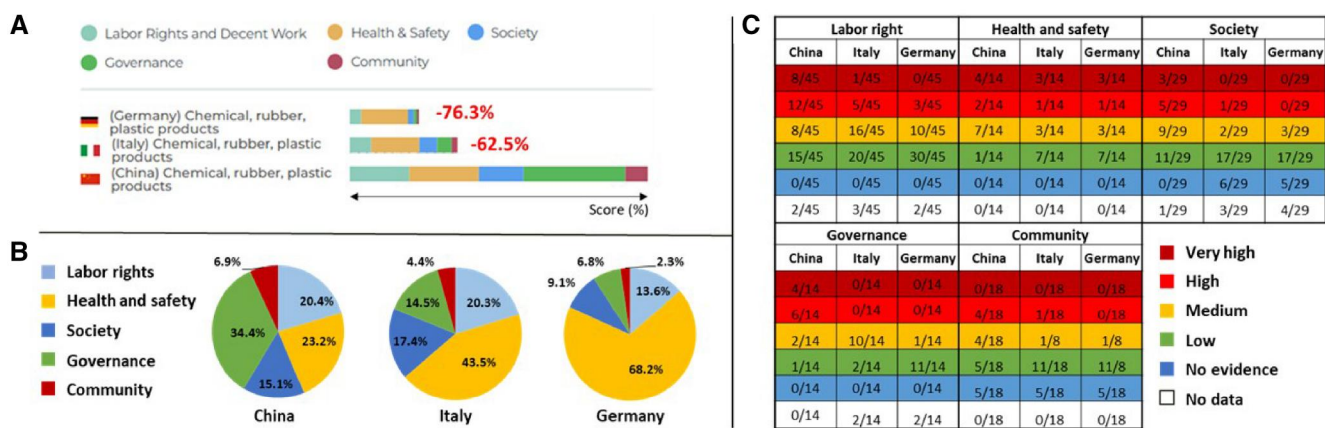


Figure 5. Percentage breakdown (A), relative comparison of total and specific impacts by category for China, Italy, and Germany (B) and number of topics with the corresponding risk level in China, Italy, and Germany, by category (C).

China 9/100, indicating a lack of freedom of expression, compared to Italy (90/100) and Germany (93/100), which are significantly more aligned with the human rights standards recommended in the EU.

Literature review on S-LCA

To date of publication, the availability of S-LCA applied to the chemical sector is very limited. Pollok et al. (2021) and Nachtergaele et al. (2024) proposed a study to investigate both environmental and social impacts of isopropyl palmitate. The analyzed plant is located in Belgium, and the scope is not to provide a comparison between different geographical contexts, but rather to compare two different production synthesis (Nachtergaele et al., 2024). In our case, it was not considered useful to conduct a comparative S-LCA related to technology for two main reasons: (1) the absence of primary data and (2) the level of detail reachable by the Risk Mapping Tool, which does not allow for investigating the technologies in such a detailed way. Serreli et al. (2021) developed a study meant to comprehend the social impacts of a wastewater treatment plant. Although it is quite distant from the field of our work, it is still considered interesting due to the defined functional unit, namely “300,000 medium-risk hours.” This FU is noteworthy because it shifts the focus to social aspects, framing the results in terms of the amount of product that can be produced before reaching a defined threshold of social risk. Such an approach aligns well with the core objective of S-LCA. However, this type of FU would compromise the alignment between LCA and S-LCA, because hours are not suitable to be adopted as a FU in environmental LCA. Therefore, in studies that aim to apply both methodologies simultaneously, it would not allow for a complete normalization of sustainability results. The work provided by Cadena et al. (2019) consists of an S-LCA applied to the design of a biorefinery in the Netherlands, where the authors identified two hotspots: Occupational Health and Safety and the Local Community. Concerning the former, the authors also invite identifying the root causes of the problem by using quality tools such as the Pareto diagram or the Ishikawa diagram. This suggestion might also be adopted in future development of the presented case study. The Local Community represents a hotspot in the Chinese context, particularly with reference to the overall risk of children being out of school. Moreover, for both China and Italy, healthcare-related issues emerge as a critical area, especially regarding the availability of nurses and midwives. The authors also compared the biorefinery system with a fossil fuel system, identifying six aspects that

should be taken into consideration to improve the biorefinery’s social performance (Society End-point, Product Responsibility End-point, Injuries, Employee Welfare, Innovation and Competitiveness, and Community). These outcomes would be extremely useful for addressing improvement strategies in the specific case study, but they are not necessarily representative of the chemical sector nor the geographical context.

Proposed guidelines for the chemical sector

As with ISO 14040-14044, ISO 14075 provides a general framework, which is not specific to particular sectors such as the chemical industry. For this reason, the development of guidelines is necessary to support the construction of conceptual models applicable to a variety of case studies, ensuring methodological and interpretative consistency. The proposed analysis was conducted with the understanding that an in-depth examination of a country’s specific issues can be a time-consuming and resource-intensive process. The scarcity of available primary data makes the research akin to an “information hunt,” where data are often fragmented, not entirely representative of reality, or difficult to access due to a lack of transparency (Roche et al., 2025). Nevertheless, despite using data derived from databases, some trends, confirmed by available online reports, have been highlighted. For this reason, the authors deemed it useful to propose and disseminate a guideline including a series of operations that can be performed, in that order, to apply a preliminary S-LCA in the absence (or pending availability) of site-specific data. The key methodological steps to apply this approach to an S-LCA in the industrial chemistry sector are summarized below:

1. Identification of the target sector and chemical product. The first step involves the selection of the chemical compound under study and the relative industrial sector. In our case, “chemicals, rubber, and plastics” has been selected as most representative in the Risk Mapping Tool.
2. Localization of main production sites and selection of geographic regions. The next step is the identification of the primary geographical regions where the compound is produced. The analysis of the supply chain supports the determination of the most significant production areas. Such a definition is crucial for the social life cycle analysis, because it has been widely demonstrated that impact intensity, but also quality and reliability of social inventories, highly depends on the national and cultural contexts (Huertas-Valdivia et al., 2020). Databases such as ecoinvent provide a

detailed representation of the industrial supply chains, and references like the Kirk-Othmer Encyclopedia of Chemical Technology and/or the Ullmann's Encyclopedia of Industrial Chemistry (John Wiley & Sons, Inc., 2000) may confirm and complement the information. The regions of interest are chosen based on relevance (e.g., areas with the highest production volume) or representativeness (e.g., specific countries of interest for the study objectives). Accordingly, in our case study, China has been chosen as the representative production site.

3. Selection of relevant social reference parameters. Social parameters for evaluation are defined according to the study's scope. If focusing on a specific company, it may be preferable to evaluate social performance according to the interest of the company or by identifying sensible topics in consistency with the analyzed context (i.e., specific nation). Conversely, when dealing with a chemical being characterized by production widespread in the world or with a global market, comparing the industrial performance with international guidelines might be more appropriate.
4. Data collection: The choice between primary data (e.g., stakeholder surveys) and secondary data (e.g., risk mapping tools, databases) depends on resource availability (i.e., money and time) and data accessibility (i.e., existence of a dataset or obsolete one). When referring to primary data, a preliminary phase of stakeholder identification (internal and external) and stakeholder engagement is necessary. These steps are known to be resource-intensive and require specific expertise (Rivela et al., 2022). If, as often happens, the collection of primary data is not possible (as in the presented case study) or is only partially possible, it is necessary to refer to secondary data from databases to fill inventory gaps and to obtain preliminary information that allows the analysis to be completed. Consequently, the results will be generic and provide a broad idea of national conditions, rather than being specific to a single company.
5. Measurement of social impacts. Based on the previously applied choices, (i.e., the context of the analysis and the impact categories of interest), social impacts can be calculated. Consistent with ISO 14075, this phase may favor the choice of reporting the results in the form of impact (i.e., social impact assessment) or relatively to a reference scale (i.e., social performance assessment). Both options are validated by ISO 14075 and, in the context of the chemical sector, depend on the availability of data and the statements of Goal and Scope. Setting up reference scales that can be adopted and adapted to each specific context could facilitate future analyses. The results obtained from this study could support the future development of reference scales specific to the chemical sector.
6. Interpretation of results. The final step involves analyzing the results, focusing on high-risk categories. This analysis helps identify critical areas and propose improvements or corrective actions for the studied supply chain.

Conclusions

The present study proposes the application of LCA to 11 methanol production strategies, all involving the conversion of CO₂, obtained from different supply sources, through rWGS. The obtained results are integrated into an additional model aimed at estimating the environmental impacts associated with the synthesis of propylene (MTP), identified as a chemical of particular interest for the current and future market. The results indicate a

preference for methanol produced from CO₂ and H₂ derived from renewable sources. The LCA study was subsequently extended to a preliminary S-LCA assessment, with the aim of providing a guideline to facilitate practitioners in the application of sector-specific S-LCA, in this case within the industrial chemistry sector. The results of the S-LCA model, based on information derived from databases (i.e., Risk Mapping Tool), highlighted the role of the geographical areas where production takes place, drawing attention to China, which was found to be inferior to European areas in most of the social categories considered. It should be noted that the social analysis was developed by referring to secondary sources, so a company-specific analysis in the future could highlight discrepancies with the results obtained from generic/average data and provide more accurate indications regarding the type of production (e.g., source of CO₂). In conclusion, the authors believe that the proposal of a sector-specific guideline is a step forward that could facilitate the future application of the methodology and that the integration of LCA and S-LCA proves effective in obtaining and providing stakeholders with a richer and more comprehensive perspective on the issues addressed.

Supplementary material

Supplementary material is available online at *Integrated Environmental Assessment and Management*.

Data availability

All data used to conduct the analysis are provided in the [online supplementary material](#), along with the relevant references.

Author contributions

Alice Vardaro (Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing—original draft), Francesco Arfelli (Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Writing—original draft), Fabrizio Passarini (Project administration, Supervision, Validation, Writing—review & editing), and Daniele Cespi (Conceptualization, Project administration, Resources, Supervision, Validation, Writing—review & editing)

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Conflicts of interest

None declared.

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