Interreg
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GreenChemForCE

# GreenChemForCE
# WP2

## Activity 2.1. Analysis of Carbon dioxide linear and circular

## Output 2.1: Strategy for low carbon footprint chemical industry in CE

## Deliverable 2.1.2: Strategy document

1st version

May 2026

## Obsah

# 1. Introduction and Strategic Context

## 1.1 Purpose and Scope

This Strategy (Deliverable D.2.1.2) builds directly on the findings of the WP2.1 Analysis of carbon dioxide linear and circular management in Central Europe [1]. While the Analysis provided a structured assessment of $CO_2$ emission sources, industrial structures, regulatory frameworks and technological potentials in the four participating countries (Czech Republic, Austria, Hungary and Slovenia), the present Strategy translates these analytical findings into coordinated strategic directions for WP2.

The Strategy focuses on carbon management in the chemical industry, with particular emphasis on carbon circularity, $CO_2$ utilisation (CCU), electrification, renewable carbon (including biomass), and cross-border cooperation mechanisms. It addresses both short-to-medium-term implementation measures and long-term transformation pathways consistent with EU climate and industrial policy objectives.

The geographical scope covers all four participating countries and is applicable to the wider Central European region, reflecting shared industrial structures, integrated supply chains and common regulatory frameworks [1,2].

## 1.2 European Policy and Industrial Framework

The Strategy is embedded in the evolving European regulatory and industrial landscape.

The Fit for 55 package establishes the binding objective of reducing EU greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, strengthening the EU ETS, expanding carbon pricing mechanisms, and accelerating renewable energy deployment [3]. For the chemical industry, this implies structural decarbonisation of energy supply, feedstock substitution and process innovation.

The Transition Pathway for the Chemical Industry identifies electrification, hydrogen, CCU/CCS, and circular carbon as key transformation levers and stresses the importance of cross-border industrial ecosystems [4].

The Antwerp Declaration calls for restoring competitiveness of European energy-intensive industries while safeguarding climate ambitions, emphasising affordable low-carbon energy, investment certainty and innovation scaling [5].

The Clean Industrial Deal (2025) reinforces industrial decarbonisation as a competitiveness strategy, linking climate neutrality with strategic autonomy, critical raw materials security and state aid flexibility [6]. The associated Clean Industrial State Aid Framework (CISAF) enables targeted public support for industrial decarbonisation technologies, including CCU, electrification and renewable hydrogen [7].

Cefic's iC2050 Carbon Manager framework further highlights the need for systemic carbon management across value chains, integrating carbon efficiency, circularity and substitution of fossil feedstocks [8].

Together, these policy instruments form the regulatory and financial backbone within which GreenChemForCE operates.

## 1.3 Position of GreenChemForCE and WP2

GreenChemForCE is an Interreg CENTRAL EUROPE project aimed at strengthening innovation capacity and accelerating the green transition of the chemical industry in Central Europe [2]. The project integrates technological pilots (WP1 and WP3), strategic analysis and coordination (WP2), and cross-border cooperation mechanisms.

WP2 plays a central integrative role. It builds upon:

- The analytical assessment of $CO_2$ linear and circular flows [1];
- National transition frameworks and CCUS action plans [9];
- Regional industrial ecosystems and cluster structures [2].

WP1 focuses on technological pilot actions related to material circularity and depolymerisation pathways (e.g., nylon depolymerisation and related material valorisation activities) [10]. WP3 addresses advanced chemical processes, including renewable solvents, biocatalysis, reusable catalysis systems and smart process integration [11].

WP2 ensures that these pilot actions are embedded in a coherent cross-border carbon management strategy and aligned with EU regulatory and industrial frameworks.

## 1.4 Strategic Structure of the Document

This Strategy is structured around four interdependent pillars:

1. **Economic and regulatory framework** [3,4,6]
2. **Cross-border cooperation and regional synergies** [1,2]
3. **Education, skills and capacity building** [2,8]
4. **Technology pathways for $CO_2$ emission reduction and utilisation** [1,2,7]

These pillars form the structural basis for the subsequent chapters of the Strategy. Each pillar reflects a necessary dimension of systemic carbon management: policy alignment, regional integration, human capital development, and technological transformation.

The interaction between these pillars ensures that technological solutions are economically viable, institutionally supported, regionally coordinated and operationally implementable.

## References (Chapter 1)

[1] GreenChemForCE WP2 O2.1 Analysis of carbon dioxide linear and circular management (Final Version, 13.3.2025).
[2] GreenChemForCE Project Description V2.0 and Partnership Agreement.
[3] European Commission, Fit for 55 Package (2021).
[4] European Commission & Cefic, Transition Pathway for the Chemical Industry (2023).
[5] The Antwerp Declaration for a European Industrial Deal (2024).
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[7] Clean Industrial State Aid Framework (CISAF), European Commission (2025).
[8] Cefic, The Carbon Managers – iC2050 Framework.
[9] National CCUS and transition planning documents (CZ, AT, HU, SI).
[10] GreenChemForCE WP1 Pilot Action Reports (D1.2.1).
[11] GreenChemForCE WP3 Pilot Action Reports (D3.2.1; D3.3.1).

# 2. Economic and regulatory framework for $CO_2$ management

## 2.1 National policy frameworks and long-term targets (2040–2050)

The economic and regulatory environment for $CO_2$ management in Central Europe is determined by a combination of EU climate legislation and national transition frameworks. This section summarises the key legislative and strategic instruments in Czechia, Austria, Hungary and Slovenia and evaluates the realism of 2040–2050 decarbonisation targets from a technological perspective.

The analysis draws on the EU Fit for 55 package [1], the EU ETS Directive revision [2], the Clean Industrial Deal [3], CISAF (Clean Industrial State Aid Framework) [4], the EU Industrial Carbon Management Strategy [5], and national energy and climate plans (NECPs) of the four countries [6–9].

### 2.1.1 Czech Republic – reference framework

The Czech Republic represents a structurally energy-intensive economy with a strong chemical, refining and materials base. $CO_2$ management policy is anchored in:

- National Energy and Climate Plan (NECP, updated 2024) [6]
- National CCUS Action Plan (MŽP) [10]
- State Energy Policy [11]
- National Transition Plan for the Chemical Industry (SCHP ČR) [12]
- RIS3 Strategy 2021–2027 [13]

The Czech NECP aligns with EU targets of at least –55% GHG reduction by 2030 (vs 1990) and climate neutrality by 2050. The CCUS Action Plan explicitly identifies cement, lime, refining and chemicals as hard-to-abate sectors where carbon capture will be necessary [10].

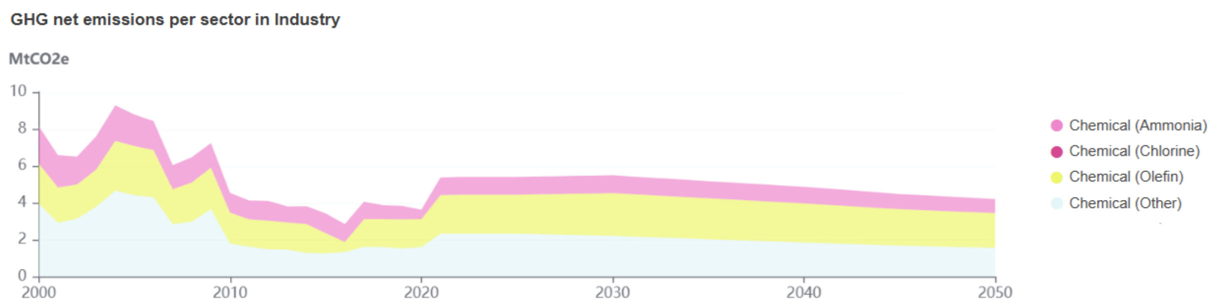


**Figure 2.1 – Structure of $CO_2$ emissions in the Czech chemical and related heavy industries**
*(Figure retained from the original Strategy / WP2 Analysis – Czech Republic.)*

**Achievability of 2040–2050 targets**

Current technologies (electrification, efficiency, partial biomass substitution) can reduce emissions significantly but **cannot fully eliminate process emissions** from:

- limestone calcination

- ammonia production (if fossil-based hydrogen remains)
- refinery off-gases

Therefore:

- Large-scale CCUS infrastructure
- Renewable hydrogen at industrial scale
- Electrified high-temperature processes
- Circular carbon feedstock systems

are indispensable.

At present, these solutions are at mixed TRL levels (6–9 for some components; 4–6 for integrated systems). Without accelerated deployment and infrastructure coordination, the 2050 target is **not achievable using currently deployed technologies alone**.

This creates a direct strategic link to technology development and capacity building under GreenChemForCE.

In addition to the policy and industrial context described above, the Czech Republic is progressively developing an implementation-oriented framework for industrial decarbonisation that extends beyond individual projects and creates conditions for long-term continuity. A key element of this framework is the emergence of the CO2 Czech Solution Group (CO2CZ), which functions as a national technological platform for carbon management and decarbonisation-oriented innovation.

The CO2CZ platform has been established as a structured coordination mechanism integrating industrial emitters, research organisations and public administration, with the objective of enabling a systemic transition towards carbon neutrality by 2050. Its activities are explicitly aligned with national strategic priorities, including RIS3 missions, and respond to European policy drivers such as the Green Deal, Fit for 55 and the evolving EU ETS framework.

From a technological and systemic perspective, the platform is based on the concept of integrated carbon management, where $CO_2$ is treated not only as an emission to be reduced, but as a managed resource within an industrial value chain. This approach encompasses the full spectrum of processes, including $CO_2$ capture, purification, transport, utilisation (CCU) and storage (CCS), and reflects the need to address decarbonisation as a system-level transformation rather than as a set of isolated technological solutions.

A defining feature of this framework is its strong orientation towards implementation. In contrast to purely analytical or strategic documents, CO2CZ activities focus on the preparation of concrete pilot and demonstration projects, including the development of pre-project documentation, feasibility assessments and technology validation. The platform actively supports the transition from research and development to industrial deployment, with the objective of increasing the technological readiness level (TRL) of key decarbonisation technologies and enabling their practical application in the Czech industrial context.

This implementation-oriented approach is supported by a broad and functionally structured ecosystem, which includes major industrial emitters (e.g. energy, cement, chemical sectors), leading research institutions and universities, and public sector representatives. The platform therefore covers the entire innovation chain, from fundamental research through applied development to industrial deployment and regulatory alignment. Such a structure enables the effective translation of research outputs into practical solutions and ensures that technological development is closely aligned with real industrial needs.

In parallel, CO2CZ contributes to the development of enabling conditions necessary for large-scale carbon management. These include, for example, the identification and mapping of $CO_2$ emission sources, the assessment of $CO_2$ quality and purification requirements, the development of transport solutions and the evaluation of storage and utilisation pathways. These activities are essential for building a functional carbon management infrastructure and correspond to the broader European objective of establishing integrated $CO_2$ networks.

An important dimension of the platform is its role in facilitating cooperation at both national and international levels. CO2CZ actively supports the involvement of Czech stakeholders in European research and innovation programmes, including Horizon Europe and Interreg, and contributes to the alignment of national activities with emerging European frameworks for industrial carbon management. This includes participation in international standardisation activities (e.g. $CO_2$ quality standards) and the development of cross-border project partnerships.

From the perspective of industrial transformation, the platform also addresses key structural challenges associated with decarbonisation. These include the need to replace fossil-based feedstocks with alternative carbon sources, the development of new value chains based on circular carbon use, and the integration of energy and material systems through Power-to-X technologies. In particular, the role of $CO_2$ as a potential feedstock for the production of synthetic fuels and chemical products represents a strategic direction for maintaining the competitiveness of the chemical industry in a low-carbon economy.

Importantly, the CO2CZ framework is not conceived as a short-term project-based initiative, but as a long-term platform with continuously evolving strategic documents, including a Strategic Research Agenda (SRA), Implementation Action Plans and technology roadmaps. These instruments are regularly updated and serve as a basis for the identification of priorities, barriers and investment needs, as well as for the coordination of stakeholders across the innovation ecosystem.

In this context, the outputs of GreenChemForCE WP2.1 can be directly embedded into an already existing and evolving implementation environment. The analytical results, strategic recommendations and identified technological pathways developed within WP2.1 are therefore not isolated outcomes but can be integrated into ongoing national processes aimed at preparing and deploying carbon management solutions.

This creates a clear pathway for continuity beyond the project duration. While GreenChemForCE provides a transnational strategic framework and analytical basis, the CO2CZ platform ensures that these results can be further developed into concrete projects, pilot implementations and investment-ready solutions within the Czech Republic. At the same time, the platform enables the transfer of knowledge and experience to other Central European regions, supporting the emergence of a broader regional carbon management ecosystem.

In a wider Central European context, similar elements of coordination between industry, research and public administration can be observed, although typically in a less integrated form. The Czech approach, represented by CO2CZ, therefore has the potential to serve as a reference model for linking strategic initiatives with implementation mechanisms, particularly in regions with strong industrial bases and emerging CCUS ambitions.

Overall, the existence of this national implementation framework significantly strengthens the long-term relevance of the GreenChemForCE Strategy. It ensures that the project contributes not only to knowledge generation and strategic alignment, but also to the gradual realisation of industrial decarbonisation pathways beyond the project lifetime, in line with both national and European climate objectives.

### 2.1.2 Austria

Austria's framework is shaped by:

- Austrian NECP: Which guides the decarbonization roadmap for carbon neutrality [7]
- Hydrogen Strategy (2022): Aims to replace up to 80% of fossil-based hydrogen consumption in energy-intensive industries with climate-neutral hydrogen by 2030.
- Transformation of Industry programme.
- The Austrian Carbon Management Strategy (CMS)
- Implementation of EU ETS and CBAM

The Austrian NECP outlines that Austria must reduce its greenhouse gas emissions by 48% by 2030. Furthermore, the decarbonization plan for the country is one of the most ambitious in the CE region, aiming for carbon-neutrality by 2040, a full decade ahead of the EU's 2050 obligation.

Austria benefits from a high share of renewable electricity (hydropower), which structurally reduces indirect emissions from electrified processes. The Austrian NECP clearly prioritizes GHG avoidance by means of incentivizing the development and transitioning away from fossil-fuel energy utilization. However, hard-to-abate industries (including refining and chemicals), which will unavoidably release CO2 and other GHGs are not discussed in detail, and only a general recommendation based on compensation strategies is presented (CCS, CCR and CCU). In this regard, carbon capture is discussed primarily for cement and waste incineration [8].

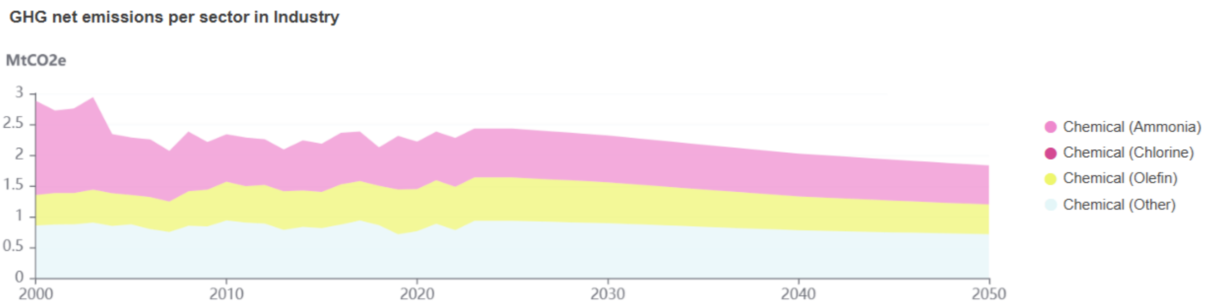


**Figure 2.2 – Emission profile of Austrian energy-intensive sectors**
*(Figure retained from the original Strategy – Austria.)*

**Achievability assessment**

Austria's renewable electricity advantage improves electrification feasibility. However:

- Hydrogen demand for full industrial decarbonisation exceeds current electrolysis capacity
- CCUS transport infrastructure is not yet operational
- Biomass availability is limited by sustainability constraints

Thus, Austria cannot reach net-zero industry solely through efficiency and electrification; cross-border hydrogen and $CO_2$ transport will be necessary. In this regard, the Austrian Carbon Management Strategy (CMS), emphasized the development of CCS, CCU and CDR strategies for the manufacturing industry to compensate for the aforementioned risks. However, CCS, CCU and CDR are complimentary strategies only after all other process efficiency and energy efficiencies are optimized first.

The joint pilot action between TU Wien and the VTL (WP 3), currently at TRL-4, contributes to Austria's NECP and CMS by advancing process optimization through biotechnological substitution of petroleum-based dyes. In line with the "mitigation and energy-efficiency first" principle, the project reduces emissions at source and supports Green Chemistry principles for the utilization of renewable inputs, mild catalysis, waste prevention, real-time monitoring, and overall safer process design. [9]

### 2.1.3 Hungary

Hungary's policy basis includes:

- Hungarian NECP [6]
- National Hydrogen Strategy
- Industrial decarbonisation white paper [16]
- Implementation of EU ETS

Hungary's chemical and fertiliser industries are structurally dependent on natural gas. Decarbonisation pathways rely heavily on hydrogen substitution and electrification.

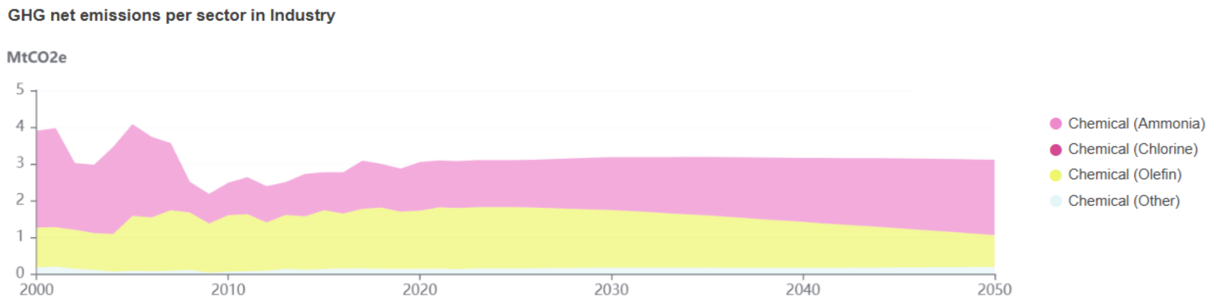


**Figure 2.3 – $CO_2$ intensity of Hungarian chemical and fertiliser production**
*(Figure retained from the original Strategy – Hungary.)*

**Achievability assessment**

Key challenges:

- Limited renewable electricity penetration
- High exposure to gas price volatility
- Lack of $CO_2$ storage infrastructure

Technological deployment at industrial scale will require:

- Regional hydrogen corridors
- Cross-border $CO_2$ transport
- Investment support via CISAF and Innovation Fund

Without accelerated technological innovation, 2040 targets are unlikely to be achieved in hard-to-abate sectors.

### 2.1.4 Slovenia

Slovenia's framework is defined by:

- Slovenian NECP [6]
- National Green Transition Strategy
- Bioeconomy orientation in industry

Slovenia has a smaller but specialised chemical sector focused on high-value products.

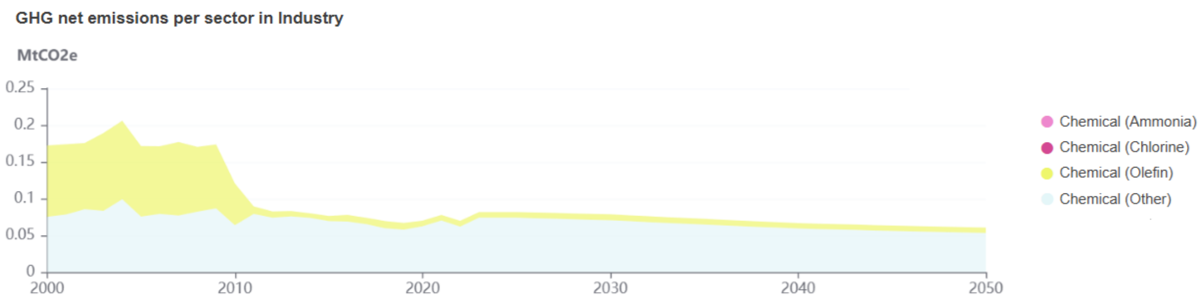


**Figure 2.4 – Emission distribution in Slovenian industrial sectors**
*(Figure retained from the original Strategy – Slovenia.)*

**Achievability assessment**

Due to smaller scale:

- CCU and bio-based substitution are more feasible in niche segments
- Large-scale CCS infrastructure is less economically viable

Slovenia's 2050 goals depend strongly on regional cooperation.

In Slovenia, the transition towards a low-carbon chemical industry is strongly influenced by the structure of its industrial base, which is characterised by smaller, highly specialised companies operating in high-value segments. This structural feature limits the feasibility of large-scale CCS deployment but creates favourable conditions for the implementation of **flexible, process-intensified and circular solutions at smaller scales**.

In parallel, Slovenia shows strong potential in **carbon capture and utilisation (CCU)** through integration into existing industrial processes rather than through standalone infrastructure. Activities within WP2, particularly in cooperation with Belinka Perkemija, demonstrate the applicability of **microstructured systems, intensified gas–liquid systems and biocatalytic conversion routes** for $CO_2$ utilisation at TRL3–4 levels. These approaches are aligned with Slovenia's innovation-driven industrial profile and allow for the development of niche CCU applications with high added value.

Due to the absence of large emission clusters and geological storage capacity, **CCS deployment remains structurally limited**, reinforcing the strategic importance of CCU, circular carbon use and renewable feedstocks. As a result, Slovenia's pathway towards 2050 climate neutrality will depend on:

- **cross-border integration within Central Europe**,
- **participation in regional value chains**,
- and **technology transfer between research institutions and industry**.

In this context, Slovenia is positioned not as a large-scale deployment hub, but as a **development and demonstration environment for innovative, intensified and circular chemical processes**, contributing to the broader regional carbon management strategy of GreenChemForCE.

## 2.2. Cross-country synthesis: Are 2040–2050 targets achievable?

The legislative frameworks presented above establish ambitious decarbonisation targets for 2040 and full climate neutrality by 2050 across the four participating countries. However, a central strategic question remains:

**Are these targets achievable with currently available technologies?**

The short and evidence-based answer is: **not fully.**

### Technological readiness gap

According to the Czech *Akční plán rozvoje CCUS* (2024), large-scale deployment of carbon capture and storage (CCS) infrastructure in the Czech Republic requires:

- new transport networks,
- cross-border $CO_2$ routing,
- regulatory adjustments for storage and utilisation,
- and long-term financial mechanisms for investment security [18].

The document explicitly states that CCUS deployment in Czech industry before 2030 will remain limited to preparatory and pilot-scale activities, with full system integration expected only after 2035 [18].

Similarly, the OECD report on Carbon Management underlines that achieving net-zero in hard-to-abate sectors (including chemicals) requires a combination of:

- CCUS,
- low-carbon hydrogen,
- electrification,
- and circular carbon strategies,
  none of which are currently deployed at sufficient scale in Central Europe [19].

The CEFIC *Transition Pathway for the Chemical Industry* confirms that the transformation towards renewable carbon feedstocks and CCU integration demands accelerated innovation, demonstration projects and substantial public-private investment frameworks beyond existing technological maturity levels [20].

### Infrastructure and system integration constraints

A critical barrier across all four countries is infrastructure readiness.

- The Czech CCUS Action Plan identifies the absence of domestic $CO_2$ storage sites and dependence on cross-border transport corridors as a structural limitation [18].
- Austria is progressing in hydrogen strategy and industrial electrification, but cross-border $CO_2$ transport remains under development.
- Hungary and Slovenia face scale constraints and limited integration of hydrogen or CCU infrastructure into industrial clusters.

The EU Clean Industrial Deal (2025) acknowledges this systemic gap and calls for coordinated infrastructure planning under TEN-E and hydrogen backbone initiatives [21].

Without such integration, the 2040–2050 decarbonisation trajectory cannot be achieved solely through incremental efficiency improvements.

### Economic feasibility

Even where technologies exist, cost remains a major constraint.

The Clean Industrial State Aid Framework (CISAF) explicitly recognises that low-carbon industrial investments require:

- state support mechanisms,
- carbon contracts for difference (CCfDs),
- and risk-sharing instruments [22].

This confirms that current market conditions alone are insufficient to drive transformation at the required speed.

### Strategic conclusion for policy makers

From a strategic perspective, the 2040–2050 targets are:

- **Politically defined and directionally correct**
- **Technically feasible in principle**
- **Not achievable without accelerated innovation and deployment**

This leads to three structural implications:

1. Existing technologies (energy efficiency, electrification, renewable electricity) are necessary but insufficient.
2. Breakthrough development in CCUS, renewable carbon chemistry and hydrogen integration is required.
3. Education, research capacity and cross-border collaboration are essential enabling conditions.

For this reason, the GreenChemForCE Strategy does not treat decarbonisation as a purely regulatory issue, but as a **technology-driven transformation supported by policy frameworks**.

The following chapter therefore moves from regulatory assessment toward pilot actions and cross-border implementation under WP2.

## References (Chapter 2)

[1] European Commission (2021). *Fit for 55 Package: Delivering the EU's 2030 Climate Target on the way to climate neutrality*. Brussels.

[2] European Parliament and Council (2023). Directive (EU) 2023/959 amending Directive 2003/87/EC establishing the EU Emissions Trading System and Decision (EU) 2015/1814. Official Journal of the European Union, L 130, 16.5.2023.

[3] European Commission (2025). Communication on the Clean Industrial Deal for competitiveness and decarbonisation in the EU. COM(2025) 85 final, Brussels, 26.2.2025.

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(Tato citace doplňuje chybějící 15 a logicky navazuje na rámec $CO_2$ managementu v kapitole 2.)
[18] OECD (2023). Carbon Management: Managing Carbon for Net Zero. OECD Publishing, Paris.
[21] CEFIC (2023). Transition Pathway for the Chemical Industry. Brussels.
[22] European Commission (2024). Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action – NECP implementation reports and guidance. Brussels.

# 3. Cross-border collaboration as a strategic instrument of WP2.1

Cross-border collaboration within GreenChemForCE is not treated merely as a formal requirement of the Interreg programme. In the context of WP2.1 – *Analysis and Strategy* – it represents a structural instrument for enabling credible, regionally coherent carbon management pathways. WP2.1 does not implement technological pilots directly; instead, it evaluates the economic, regulatory and technological feasibility of $CO_2$ management solutions across Central Europe. In doing so, it must reflect the reality that industrial decarbonisation cannot be implemented within isolated national frameworks.

The broader European policy environment confirms this necessity. The Fit for 55 Package [1], the revised EU ETS Directive [2], the Clean Industrial Deal [3], the Clean Industrial State Aid Framework (CISAF) [4], and the Industrial Carbon Management Strategy [5] all emphasise coordinated, cross-border approaches to industrial transformation. Carbon pricing, state aid rules, infrastructure development and industrial carbon management are designed at EU level and require harmonised implementation across Member States. National Energy and Climate Plans of the Czech Republic, Austria, Hungary and Slovenia [6–9] reflect ambitious decarbonisation trajectories towards 2040–2050, yet they also reveal structural asymmetries in industrial composition, renewable energy availability and technological maturity.

WP2.1 therefore approaches cross-border collaboration not as an additional layer of cooperation, but as a strategic condition for the credibility of regional $CO_2$ management pathways. The analytical work carried out within WP2.1 indicates that current commercially available technologies are insufficient to achieve long-term climate neutrality targets in energy-intensive chemical sectors without accelerated innovation, coordinated validation and harmonised regulatory interpretation. In this context, cross-border integration reduces duplication of effort, enhances validation capacity and strengthens the robustness of policy recommendations.

Within WP2.1, the most strategically relevant cross-border configuration is the Czech Republic–Hungary axis. This cooperation connects Charles University in Prague, which focuses on renewable carbon chemistry, molecular design of $CO_2$-derived and bio-based intermediates and strategic carbon management analysis, with Servier Research Institute of Medicinal Chemistry (SRIMC), Hungarian applied research and industrial validation capacities. The cooperation forms an innovation loop in which renewable carbon pathways identified and analysed in the Czech research environment are tested and validated within Hungarian pharmaceutical and fine chemical contexts. The results are then reassessed within the WP2.1 strategic framework, considering regulatory implications under EU ETS [2], eligibility under CISAF [4], and alignment with national NECP commitments [6,8].

This configuration transforms cross-border interaction into a strategic validation mechanism. It demonstrates how academic research in one Member State can be industrially assessed in another, thereby reducing technological uncertainty and strengthening the evidence base for policy makers. Rather than presenting national pilots as separate achievements, WP2.1 frames the CZ–HU cooperation as an integrated regional pathway supporting the implementation logic of the Industrial Carbon Management Strategy [5].

Austria and Slovenia contribute complementary capacities within GreenChemForCE, and their participation remains structurally important. However, in the specific context of WP2.1, the Czech–Hungarian cooperation constitutes the core cross-border reference model. It provides a tangible example of how renewable carbon substitution, $CO_2$ utilisation and regulatory feasibility assessment can be synchronised across borders in support of long-term industrial decarbonisation objectives.

To illustrate this architecture, the following network representation should be included:

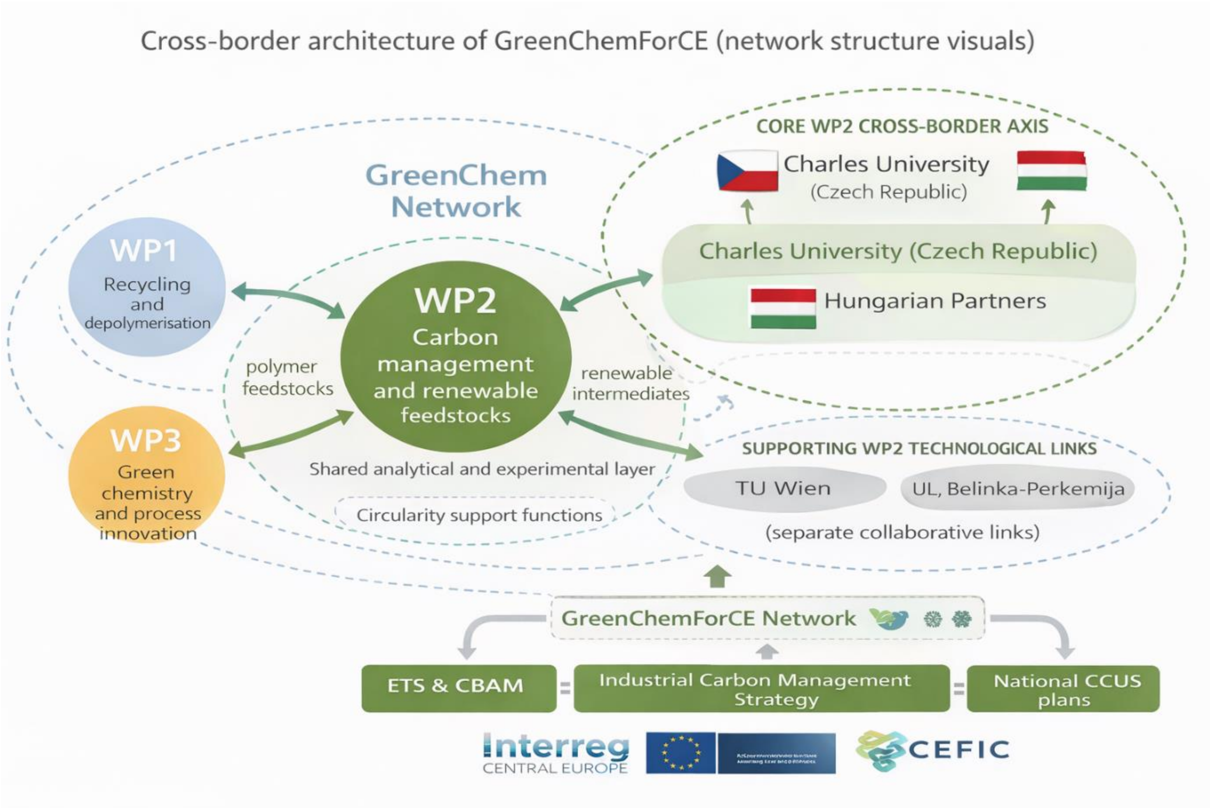


**Figure 3.1 – Cross-border architecture of GreenChemForCE with highlighted WP2 core axis (CZ–HU)**

From a strategic perspective, WP2.1 must also address the fundamental question emerging from national climate strategies: are the 2040–2050 decarbonisation targets achievable using currently deployed technologies? The synthesis of NECP commitments [6–9], EU-level policy frameworks [1–5], and WP2.1 analytical findings suggests that the answer is conditional. Electrification, renewable energy expansion and incremental efficiency improvements are necessary but not sufficient. Industrial carbon management, including $CO_2$ utilisation, renewable carbon substitution and systemic process integration, requires further technological development and coordinated scaling.

In this context, cross-border collaboration becomes a risk-mitigation mechanism. It accelerates technology maturation by enabling joint experimentation, shared datasets and industrial validation across jurisdictions. It also supports regulatory convergence by exposing practical implementation challenges early in the development phase. WP2.1 thus treats cross-border cooperation as an enabling layer for both technological advancement and policy coherence.

For policy makers, the strategic implication is clear: regional carbon management strategies must be designed with cross-border integration in mind. Investment support mechanisms under CISAF [4], carbon pricing signals under the EU ETS [2], and infrastructure planning under the Industrial Carbon Management framework [5] all benefit from transnational alignment. The CZ–HU cooperation within WP2.1 offers a scalable reference model for such alignment in Central Europe.

Cross-border collaboration, as articulated in this chapter, therefore serves not only as a project feature but as a structural element of the WP2.1 Strategy. It operationalises EU-level policy ambitions within a regional innovation ecosystem and provides an evidence-based pathway for translating analytical findings into coordinated industrial transformation.

## **References** (Chapter 3)

[1] European Commission (2021). Fit for 55 Package: Delivering the EU's 2030 Climate Target on the way to climate neutrality. Brussels.

[2] European Parliament and Council (2023). Directive (EU) 2023/959 amending Directive 2003/87/EC establishing the EU Emissions Trading System and Decision (EU) 2015/1814. Official Journal of the European Union, L 130, 16.5.2023.

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[8] Government of Hungary (2024). Updated National Energy and Climate Plan.

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# 4. Green Chemistry Education and Research in Central Europe: A Comparative Overview

## 4.1. Introduction

**The strategic educational and research framework presented here is aligned across all Work Packages of the GreenChemForCE project and is formulated in a consistent manner within all three strategic reports. In this version, particular emphasis is placed on Green Chemistry approaches related to the circular management of carbon dioxide and broader decarbonization strategies.**

Green Chemistry is becoming an essential pillar in modern chemical education and research, driven by the global transition toward sustainability, circular economy principles, and low-carbon technologies. Universities across Europe are integrating these concepts into their academic and research frameworks in different ways—ranging from dedicated degree programmes to research-driven approaches and embedded curricular elements. The recommendation of this strategic pillar is the strengthening of the educational aspect (most importantly on academic level) in a global context, and with particular emphasis on Central European Region. To achieve this, the action plan is developed across the academic institutions involved in the GreenChemForCE project. This includes comparing the levels of the academic knowledge and approaches between universities involved in GreenChemForCE project, cross-border exchange of the knowledge and adapting the curricula at the institutions with lower level of involvement of the green chemistry. As such, this approach fulfils the requirement of InterregCE programme.

This overview highlights four institutional models represented by TU Wien (in collaboration with University of Vienna and BOKU University), Eötvös Loránd University, University of Ljubljana, and Charles University in Prague. Within the representation of models for each institution, the final subchapter highlights the aspects related to carbon dioxide. The analysis reveals that TU Wien represents the most advanced and structurally developed model of Green Chemistry integration, followed by University of Ljubljana and Eötvös Loránd University, while Charles University currently shows only limited and indirect engagement with the field. Against this background, an action plan aimed at strengthening and systematizing Green Chemistry education and research at Charles University is proposed.

## 4.2. Dedicated University Programs

### 4.2.1: Dedicated Green Chemistry Degree Programmes (Vienna Model)

**a) Masters's Programme**

The joint Master's programme in Green Chemistry offered by TU Wien, the University of Vienna, and BOKU represents a fully structured and interdisciplinary educational model.

### Programme Motivation and Goals

The programme is designed in response to the transformation of the chemical industry from fossil-based systems toward sustainable, circular processes. It positions chemistry as a key contributor to environmental solutions.

Graduates are trained to:

- Design energy- and resource-efficient processes
- Evaluate environmental impacts using Life Cycle Assessment (LCA)
- Integrate chemistry with biotechnology and process engineering

### Curriculum Structure

(120 ECTS, 4 semesters, English-taught) combines expertise from all three universities and includes:

- Core subjects (50–60 ECTS)
- Electives (20–30 ECTS)
- Soft skills (10 ECTS)
- Master's thesis (30 ECTS)

Core Modules (Selection)

- Green Synthesis & Catalysis: Modern synthetic methods, photochemistry, and electrochemistry.
- Sustainable Polymers & Materials: Developing biodegradable or highly recyclable plastics.
- Renewable Raw Materials: Chemistry of biomass, $CO_2$ as a feedstock, and the utilization of waste streams.
- Process Engineering & Technology: Scaling up processes ("scale-up") with a focus on green parameters.
- Sustainability Assessment: Tools for the ecological and economic evaluation of chemical processes.

### Special Features

- Interdisciplinary enrolment across three institutions
- Strong industry collaboration in Vienna
- Innovation-driven "Benign by Design" philosophy

### b) PhD Programme

The corresponding PhD programme (180 ECTS, 3 years) focuses on original research aimed at decarbonizing the chemical industry. Key research areas include:

- Advanced catalysis
- Circular chemical processes
- Green solvents (e.g., ionic liquids, deep eutectic solvents)
- Biorefinery concepts

Doctoral candidates typically work on funded research projects and contribute to scientific publications while engaging in international collaborations.

**c) Vienna model in the context of WP2.**

Across the Master's and PhD programmes in Green Chemistry at TU Wien, University of Vienna, and BOKU University, $CO_2$ is treated as both a sustainability challenge and a chemical resource within a circular carbon framework.

- **Master's level:** $CO_2$ is introduced as a renewable feedstock within green synthesis and circular chemistry concepts
- It is considered in sustainable process design, catalysis, and environmental assessment (LCA)
- Focus on integrating $CO_2$ into broader renewable carbon strategies (alongside biomass)
- **PhD level:** $CO_2$ is a central research target for chemical innovation
- Development of catalytic and electrocatalytic methods for $CO_2$ conversion
- Transformation of $CO_2$ into value-added chemicals and functional materials

Overall, the programmes shift the perspective from $CO_2$ as an emission to be reduced toward $CO_2$ as a usable building block in a circular carbon economy.

### 4.2.2 Integrated Curriculum Approach (Ljubljana Model)

At University of Ljubljana, Faculty of Chemistry and Chemical Technology (UL FKKT), Green Chemistry is broadly embedded across teaching, research, and industry collaboration.

**a) Curriculum Integration**

Green Chemistry concepts are incorporated at all levels:

- **Bachelor level:** Introduced within environmental chemistry, process engineering, and industrial chemistry courses
- **Master level:** Advanced topics include:
  - Green reaction engineering
  - Sustainable catalysis
  - Alternative solvents
  - Process intensification and flow chemistry
  - Microreactor and microfluidic technologies

Recent curriculum modernization initiatives have further strengthened sustainability-focused and interdisciplinary modules.

**b) Research-Based Education**

Students actively engage in research areas such as:

- $CO_2$ capture and utilization
- Polymer recycling and circular materials
- Biomass valorization
- Green oxidant production
- Intensified chemical processes

Research groups in catalysis, reaction engineering, environmental chemistry, and microprocess engineering play a central role in education.

#### c) Student Involvement and Scale

- 250–300 BSc students
- 120–150 MSc students
- 60–80 PhD students
- More than 50% exposed to Green Chemistry concepts

Students participate in:

- Thesis projects
- National and international research programmes (e.g., Horizon Europe, Interreg)
- Industry collaborations

#### d) Industry and Lifelong Learning

UL FKKT emphasizes knowledge transfer through:

- Micro-credential programmes
- Professional training modules
- Industry-focused case studies (e.g., hydrogen peroxide production, polymer recycling)

#### e) Ljubljana model in the context of WP2.

- $CO_2$ is integrated across **education, research, and thesis work** as part of broader Green Chemistry training
- Strong emphasis on **$CO_2$ capture and utilization (CCU)** within chemical engineering and catalysis courses
- $CO_2$ is addressed as part of **circular economy and sustainable process design** approaches
- Thesis and research topics include:
    - $CO_2$ capture and conversion technologies
    - Catalytic and process-based $CO_2$ utilization
    - Integration of $CO_2$ into intensified and sustainable chemical processes
- Research groups support **applied $CO_2$ valorization**, linking fundamental chemistry with engineering solutions
- Student involvement in **national and EU-funded projects (e.g., Horizon Europe)** enables practical work on $CO_2$-related technologies
- Overall approach: $CO_2$ is treated not only as an emission, but as a **resource integrated into circular chemical systems and industrial applications**

### 4.2.3. Research-Driven Green Chemistry Education (Budapest Model)

At Eötvös Loránd University, Green Chemistry is primarily integrated through research rather than formal coursework.

#### a) Curriculum Integration

Currently, there are no dedicated Green Chemistry courses at the BSc, MSc, or PhD levels. Instead, sustainability concepts are introduced through:

- Laboratory work
- Research projects
- Applied thesis topics

**b) Research and Thesis Opportunities**

Students can engage in Green Chemistry through thesis work, particularly within the Catalysis and Organic Synthesis Research Group. Research areas include:

- Sustainable catalysis (e.g., micellar catalysis)
- Environmentally benign synthetic methodologies

**c) Student Participation**

Engagement is highly specialized:

- Approximately 2–3% of MSc students of the Chemistry institute are involved in Green Chemistry topics.

**d) Institutional Perspective**

This model reflects a strong research foundation but limited curricular visibility. It offers flexibility and depth in specialized topics, while indicating potential for future expansion into formal coursework.

**e) Budapest model in the context of WP2.**

$CO_2$-related Green Chemistry activities at Eötvös Loránd University are not supported by dedicated staff or a structured institutional framework.
Engagement may occur only indirectly through individual research projects in catalysis and organic synthesis.
Overall, $CO_2$ valorization is not an established or coordinated focus area within the institution.

### 4.2.4. Limited Institutional Presence of Green Chemistry (Prague Model – Charles University)

**a) Green chemistry aspects at CU**

At Charles University, Green Chemistry currently has only a limited and largely indirect presence within the academic structure. Unlike more integrated or curriculum-based models, there are no dedicated Green Chemistry courses in the official study programmes, and even closely related subjects—such as environmental chemistry—are not systematically included in the core course list for chemistry students. Engagement with sustainability concepts therefore depends almost entirely on research activities. However, these are typically centered on general catalysis, organic synthesis, or materials chemistry without an explicit Green Chemistry focus or dedicated laboratory infrastructure. The absence of specialized research groups or laboratories oriented specifically toward Green Chemistry further reduces its visibility as a distinct field. As a result, while students may encounter isolated elements of sustainable chemistry within broader research contexts, there is no coherent educational or institutional framework that supports Green Chemistry as a defined area of study.

**b) Prague model in the context of WP2.**

$CO_2$-related Green Chemistry activities at Eötvös Loránd University are not supported by dedicated staff or a structured institutional framework.

Engagement may occur only indirectly through individual research projects in catalysis and organic synthesis.

Overall, $CO_2$ valorization is not an established or coordinated focus area within the institution.

### 4.2.5. Comparative Insights

These three institutional approaches illustrate distinct strategies for integrating Green Chemistry:

- **Vienna model:** Fully structured, interdisciplinary degree programmes with strong industry links
- **Ljubljana model:** Broad curricular integration combined with strong research and industry engagement
- **Budapest model:** Research-driven specialization with limited formal coursework
- **Prague model:** Limited institutional presence of Green Chemistry, research-driven specialization with limited formal coursework

## 4.3 Action Plan for Introducing Green Chemistry at Charles University

The introduction of Green Chemistry should follow a focused, stepwise approach that builds on existing strengths while gradually establishing a visible institutional framework.

### 4.3.1. Mapping of Existing Expertise

The initial step involves identifying and consolidating existing expertise across current courses and research groups. Particular attention should be given to areas such as catalysis, organic synthesis, materials chemistry, and process chemistry where Green Chemistry principles are already implicitly present.

This mapping will:

- Reveal internal capacity for teaching and supervision
- Enable coordination between departments
- Provide a foundation for curriculum development

**Time frame:** The mapping of the expertise has been already conducted as a part of the strategy development process.

### 4.3.2. Establishment of a Dedicated Green Chemistry Course (Including $CO_2$ Circularity and Decarbonization Component)

A single specialized course in Green Chemistry should be introduced at the Master's level. This course will serve as the central educational component, providing a comprehensive foundation in Green Chemistry while incorporating thematic modules aligned with specific research areas.

One of these modules will focus on $CO_2$ circularity and decarbonization, addressing the role of chemistry in reducing greenhouse gas emissions and enabling carbon-neutral processes.

Within this framework, the $CO_2$-focused module should address:

- $CO_2$ capture, utilization, and storage (CCUS) concepts
- Catalytic conversion of $CO_2$ into value-added chemicals and fuels
- Carbon-neutral and low-carbon process design
- Hydrogen economy and Power-to-X technologies
- Life Cycle Assessment (LCA) and carbon footprint analysis

The course should combine theoretical instruction with case studies and, where possible, practical or project-based components linked to current research and real-world decarbonization challenges. Its content will be coordinated by academics from TUW (PPX), and UL (PPY). This cross-border cooperation will lead to strengthening of regional educational system, relevant to chemical education and sustainability, fulfilling the definitions of the programme.

**Time frame:** The preparation of the course content will start during the duration of the project. It is expected that the curse will be launched in the academic year 2027/2028.

### 4.3.3. Establishment of a Green Chemistry Research Laboratory (Including $CO_2$ Utilization as a Key Research Direction)

A dedicated Green Chemistry research laboratory should be established to support both educational and research activities across multiple sustainability-related themes. Within this broader framework, one of the central research directions will focus on the development of catalysts and catalytic processes enabling the incorporation of $CO_2$ into organic molecules.

This research direction will include:

- Design and development of catalytic systems for $CO_2$ activation and functionalization
- Development of catalytic methodologies for $CO_2$ incorporation into organic molecules
- Utilization of biomass-derived components (as naturally captured $CO_2$ in synthesis of organic molecules
- Integration of $CO_2$ as a C1 building block in sustainable synthetic chemistry
- Process development under energy-efficient and environmentally benign conditions

These activities will be embedded within the broader agenda of the laboratory, which will also cover additional areas of Green Chemistry, including sustainable synthesis, alternative reaction media, and circular chemical processes.

**Time frame:** The establishment of the laboratory will commence during the duration of the project, with initial setup, infrastructure development, and research activities being progressively implemented. The laboratory is intended as a long-term institutional platform and will continue to operate beyond the project's completion, ensuring sustainability and fulfilling the programme conditions.

### 4.3.4. Development of Thesis Opportunities

Thesis opportunities should be systematically developed across all levels of higher education, including Bachelor's, Master's, and PhD programmes, within the Green Chemistry framework. This will ensure a continuous educational pathway closely integrated with ongoing research activities.

Within this structure, $CO_2$ valorization will represent one of the available research directions, alongside other thematic areas covered by the laboratory. Students at all levels will be able to engage in thesis projects aligned with the laboratory's research agenda, ensuring direct involvement in current scientific challenges and both fundamental and applied Green Chemistry research.

**Time frame:** Thesis activities have already been initiated, with one Bachelor's and one Master's student currently working on topics relevant to utilization of biomass-derived components. In addition, PhD thesis topics have already been opened, particularly in the area of biomass-derived component incorporation. The development of thesis opportunities will continue throughout the duration of the project and will be sustained beyond its completion, ensuring long-term integration of education and research within the Green Chemistry framework.

### 4.3.5. Expected Milestones

**Milestone 1: Completion of Expertise Mapping (Involved Partners: PP1)**

- *Status: already achieved as part of the strategy development process*

**Milestone 2: Initial Establishment of Research Laboratory (Involved Partners: PP1)**

- Allocation of space and basic infrastructure
- Definition of core research themes, including $CO_2$ utilization
- Start of pilot research activities
- *Target: End of 2026*

**Milestone 2: Operationalization of Research Activities (Involved Partners: PP1)**

- Full implementation of research directions ($CO_2$ valorization, biomass utilization, sustainable synthesis)
- Integration of laboratory activities with teaching and student training
- *Target: Beginning of 2027. Status:additional funding already secured for the research activities relevant to the topic (Marie Currie garnt Charleston), as a part of a collaborative work between PP1 (CU), and PP4 (SRIMC)*

**Milestone 3: Design of Green Chemistry Course for M.Sc. and Ph.D. students (Involved Partners: PP1)**

- Development of course syllabus and structure
- Integration of $CO_2$ circularity and decarbonization module
- Internal approval process within the institution
- *Target: finalization during 2027*

**Milestone 4: Launch of Green Chemistry Course (Involved Partners: PP1)**

- Introduction of the course into the curriculum
- *Target: Academic year 2027/2028 or 2028/2029*

**Milestone 6: Launch and Expansion of Thesis Topics (Involved Partners: PP1)**

- Opening of Bachelor's, Master's, and PhD thesis topics
- Active involvement of students in ongoing research projects
- Supervision framework established across departments
- *(Status: ongoing – initial students already engaged, PhD topics opened)*

# 5. Technologies Enabling Carbon Dioxide Management in GreenChemForCE

The transformation of the chemical industry in Central Europe requires a realistic assessment of technological readiness in relation to the decarbonisation targets set for 2040 and 2050 under the EU climate framework. The Fit for 55 package, the revision of the EU Emissions Trading System, the Industrial Carbon Management Strategy and the Clean Industrial Deal collectively establish a clear regulatory trajectory towards climate neutrality [1–4]. However, regulatory ambition alone does not guarantee technological feasibility. The central question for WP2.1 of GreenChemForCE is therefore whether currently available technologies can deliver deep emission reductions within the structural, economic and infrastructural conditions of the participating countries.

The technological logic of carbon dioxide management in the chemical industry follows a hierarchical structure, originally analysed within WP2.1. This hierarchy is preserved in the triangular representation reproduced in the original Strategy.

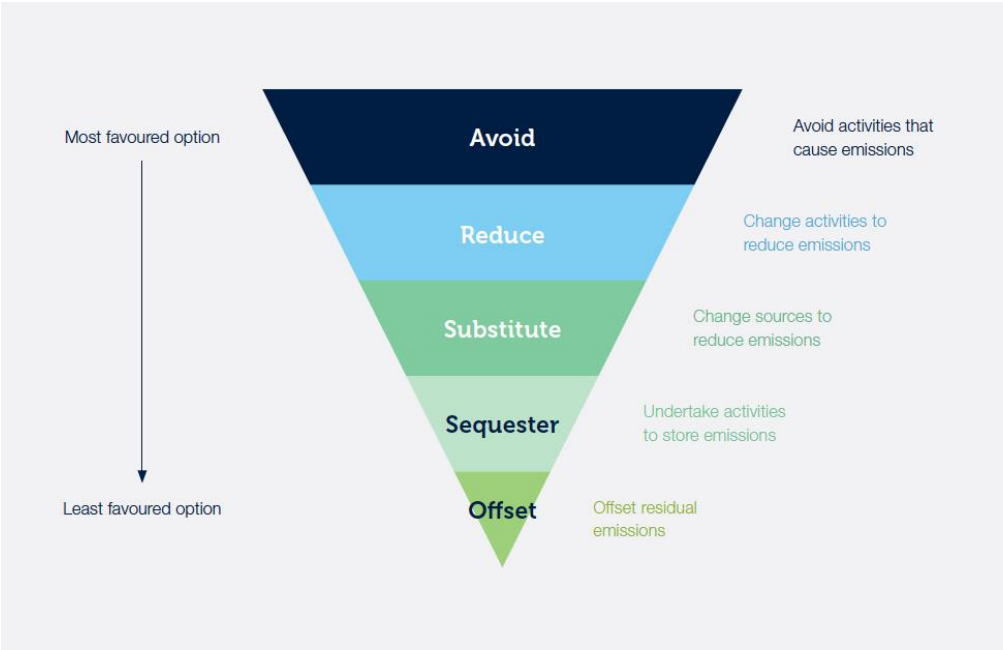


**Figure 5.1 – Hierarchy of technological approaches for carbon dioxide management in the chemical industry (triangular representation)**
*Source: adapted from GreenChemForCE WP2.1 Analysis; CEFIC iC2050 Carbon Manager framework.*

The hierarchy demonstrates that emission prevention and energy efficiency form the structural base of decarbonisation. Above this level, fuel substitution and electrification contribute to incremental reductions. Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) represent higher-order interventions addressing unavoidable process emissions. At the apex lies circular carbon integration, where $CO_2$ is embedded into sustainable material cycles rather than treated solely as waste.

Industrial analysis conducted within WP2.1 confirms that certain emission sources—particularly lime calcination, ammonia production, refinery processes and others—cannot be eliminated through efficiency measures alone [5]. Consequently, structural decarbonisation requires the deployment of capture technologies and carbon circularity mechanisms. This conclusion is fully aligned with the European Industrial Carbon Management Strategy [4].

A fundamental paradigm shift reflected in both European policy and the WP2 analysis is the recognition of $CO_2$ as a potential feedstock. The figure reproduced below illustrates the integration of $CO_2$ into chemical value chains.

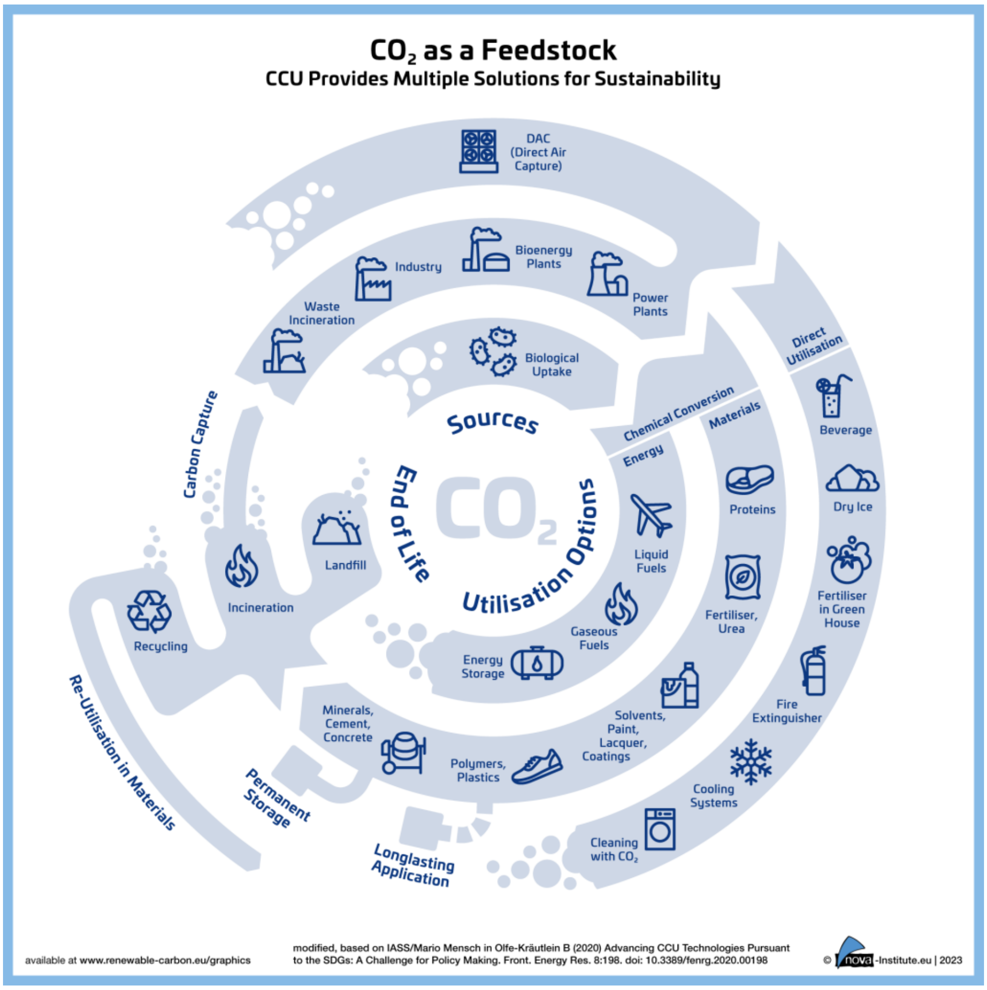


**Figure 5.2 – $CO_2$ as feedstock in the carbon value chain**
*Source: nova-Institute (2023), adapted from peer-reviewed CCU literature and policy-oriented CCU overviews.*

This representation highlights pathways through which captured $CO_2$ may enter chemical production, including hydrogenation routes and intermediate synthesis. The feasibility of these pathways depends critically on renewable hydrogen availability and electricity system decarbonisation. Without these enabling conditions, CCU risks remaining carbon-neutral at best, rather than carbon-negative. The Clean Industrial Deal explicitly acknowledges this systemic dependency [3].

The strategic distinction between conventional and bio-integrated CCU systems is further analysed in the following comparative diagram from the original document.

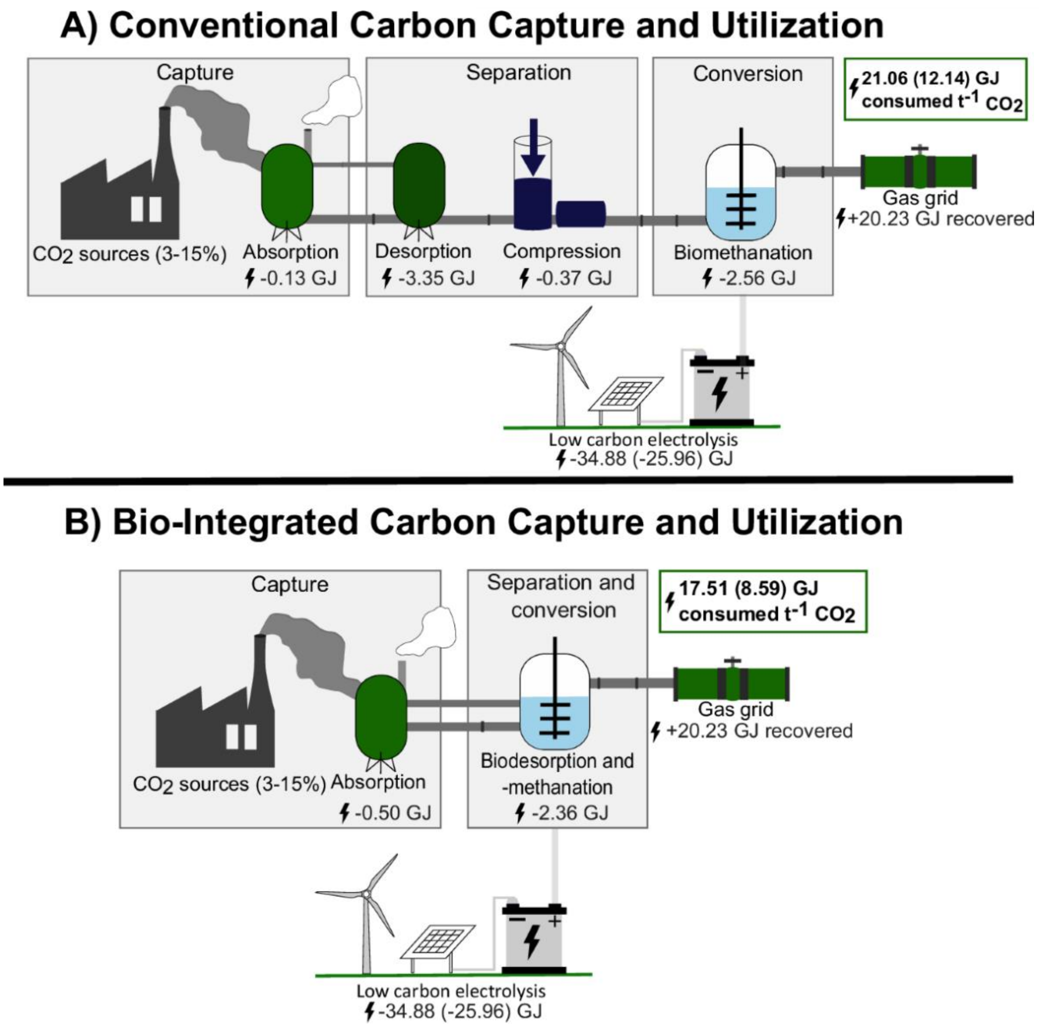


**Figure 5.3 – Comparison of conventional CCU system vs bio-integrated CCU system**
*A) Conventional carbon capture and utilisation*
*B) Bio-integrated carbon capture and utilisation*
*Source: adapted from peer-reviewed CCU and LCA literature; schematic representation without quantitative values.*

The comparison shows that conventional CCU often remains dependent on fossil-based hydrogen inputs, whereas bio-integrated systems combine renewable hydrogen, biomass-derived intermediates and circular carbon flows. For WP2, this distinction is decisive. The Czech–Hungarian cooperation involving Charles University and Hungarian research partners focuses specifically on catalytic $CO_2$ transformation and renewable building blocks, thereby aligning more closely with the bio-integrated model.

Carbon management cannot be evaluated in isolation from the broader chemical value chain. The systemic perspective presented in the original Strategy is retained below.

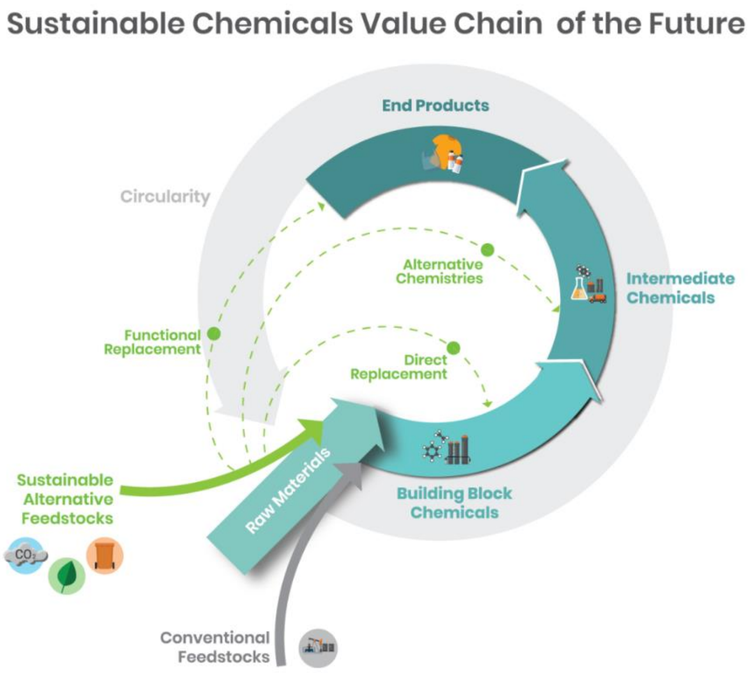


**Figure 5.4 – Sustainable Chemicals Value Chain**
*Source: CEFIC – Transition Pathway for the Chemical Industry / iC2050 background material.*

This framework links feedstock origin, industrial processing, product use and recycling, illustrating that technological intervention must occur at multiple stages simultaneously. The circular carbon perspective is further reinforced by the following figures.

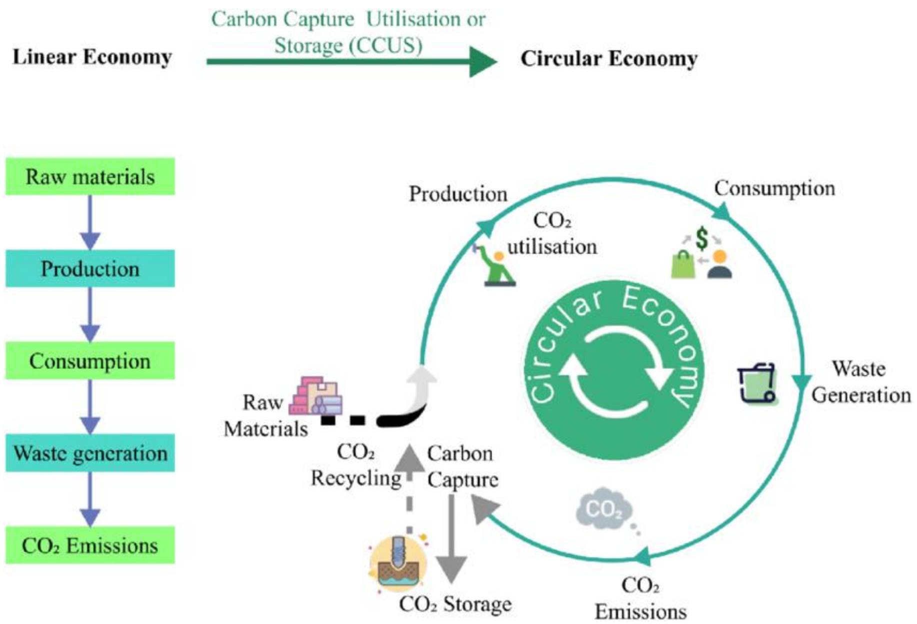


**Figure 5.5 – Carbon dioxide cycle in chemical production**
*Source: adapted from GreenChemForCE WP2.1 Analysis; EU Industrial Carbon Management framework.*

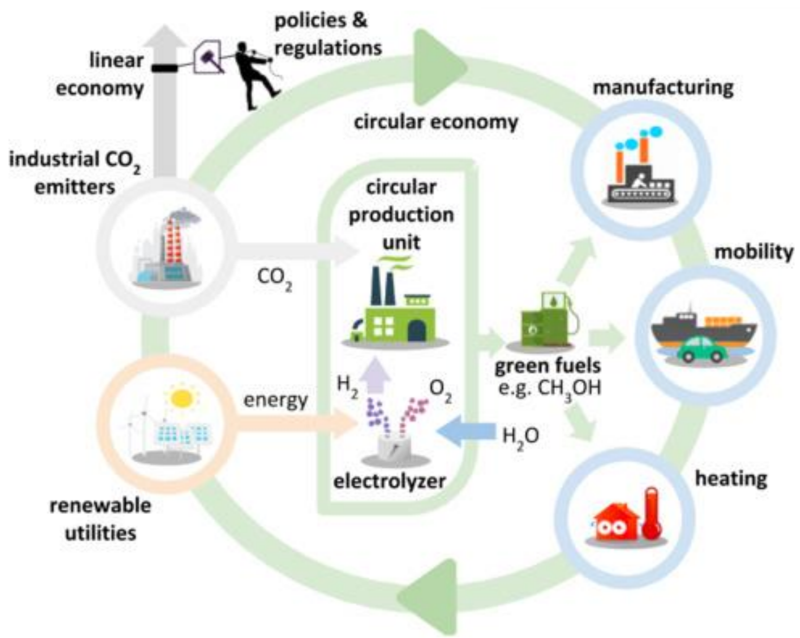


**Figure 5.6 – Carbon circularity concept**
*Source: adapted from EU Circular Economy Action Plan and Industrial Carbon Management policy documents.*

Together, these diagrams emphasise that full decarbonisation requires integration between capture, utilisation, renewable energy systems and material recycling. They also reveal structural gaps in Central Europe: insufficient $CO_2$ transport networks, limited geological storage options, and uneven hydrogen infrastructure development. The Czech CCUS Action Plan and related analyses confirm that these infrastructure constraints remain unresolved [5].

When assessed against the 2040–2050 climate neutrality horizon, current mature technologies—although available at high TRL for post-combustion capture and certain CCU pathways—cannot by themselves deliver full decarbonisation at the required speed and scale. Electrification of high-temperature processes, large-scale renewable hydrogen deployment and cross-border $CO_2$ infrastructure remain at varying stages of development. The systemic barrier analysis presented illustrates regulatory, economic and technological constraints that persist across the region.

The strategic role of GreenChemForCE WP2 must therefore be understood not as infrastructure deployment, but as technology validation and readiness acceleration. By raising the TRL of catalytic $CO_2$ conversion routes, integrating renewable building blocks and strengthening cross-border research cooperation—particularly between Czech and Hungarian partners—WP2 contributes to narrowing the deployment gap identified at European level [2–4].

In this context, the targets for 2040–2050 are not achievable solely with currently mature technologies. They require accelerated innovation, systemic coordination and transnational knowledge exchange. GreenChemForCE provides a regional platform through which such acceleration can occur in a structured and policy-aligned manner.

## Conclusion – Chapter 5

The analysis presented in this chapter confirms that carbon dioxide management in Central European chemistry cannot rely on a single technological solution. The transition towards 2040–2050 climate neutrality objectives, as framed by the EU Industrial Carbon Management Strategy, the revised EU ETS and the Clean Industrial Deal [6 - 8], requires a structured combination of emission prevention, circular carbon integration, carbon capture and selective utilisation pathways.

The technological hierarchy illustrated in Figures 5.1–5.6 demonstrates that efficiency improvements and material circularity form the necessary foundation. However, the persistence of unavoidable process emissions — particularly in ammonia production, lime processing and refining — structurally necessitates the deployment of CCS and CCU technologies. Current Technology Readiness Levels confirm that while selected capture technologies are approaching commercial maturity, catalytic $CO_2$ valorisation pathways and integrated renewable hydrogen systems still require accelerated development and system alignment.

Within this context, WP2.1 of GreenChemForCE does not aim to build large-scale infrastructure. Its strategic role lies in increasing technological readiness, validating catalytic pathways and strengthening cross-border knowledge integration, particularly within the Czech Republic–Hungary cooperation framework. This contribution is complementary to broader policy instruments and national CCUS action plans [9, 10].

The assessment leads to a clear conclusion:

Full achievement of 2040–2050 decarbonisation targets in Central Europe is not feasible solely with currently deployed technologies. It requires coordinated technological innovation, renewable energy expansion, infrastructure development and systemic industrial integration.

Additional emerging and enabling pathways that may become strategically relevant for WP2 in the medium to long term are outlined in **Appendix 1**, where renewable carbon feedstocks, circular carbon integration and advanced process intensification options are discussed in greater detail. These pathways should be considered as part of a dynamic strategic portfolio rather than fixed technological commitments.

GreenChemForCE therefore positions WP2 as a technology-readiness accelerator within a broader European carbon management transformation framework.

## References (Chapter 5)

[1] European Commission (2021). *Fit for 55 Package: Delivering the EU's 2030 Climate Target on the way to climate neutrality*. Brussels.

[2] European Parliament and Council (2023). *Directive (EU) 2023/959 amending Directive 2003/87/EC establishing the EU Emissions Trading System*. Official Journal of the European Union, L 130, 16.5.2023.

[3] European Commission (2025). *Communication on the Clean Industrial Deal for competitiveness and decarbonisation in the EU*. COM(2025) 85 final, Brussels, 26.2.2025.

[4] European Commission (2024). *Communication on Industrial Carbon Management*. Brussels.

[5] Ministry of the Environment of the Czech Republic (2024). *Akční plán rozvoje CCUS v České republice*. Prague.

[6] European Commission (2024). Communication on Industrial Carbon Management. Brussels.

[7] European Parliament and Council (2023). Directive (EU) 2023/959 amending Directive 2003/87/EC establishing the EU Emissions Trading System. Official Journal of the European Union, L 130, 16.5.2023.
[8] European Commission (2025). Communication on the Clean Industrial Deal for competitiveness and decarbonisation in the EU. COM(2025) 85 final, Brussels, 26.2.2025.
[9] Ministry of the Environment of the Czech Republic (2024). Akční plán rozvoje CCUS.
[10] CO2CZ (2026). AP Dekarbonizace 2050 – revised version after Steering Committee 13.2.2026.

# Appendix 1

Strategically Relevant Emerging Pathways for WP2.1

While Chapter 5 defines the currently actionable technology structure for WP2.1, this Appendix outlines additional pathways that are strategically relevant for long-term carbon management in Central Europe. These directions reflect technological trajectories that must be monitored and gradually integrated if 2040–2050 objectives are to remain credible under EU industrial carbon policy frameworks [1-4].

## A. Renewable and Non-Fossil Carbon Feedstocks

The structural transformation of the chemical industry requires progressive substitution of fossil carbon with renewable and circular sources, including $CO_2$, biomass-derived intermediates and recycled carbon streams.

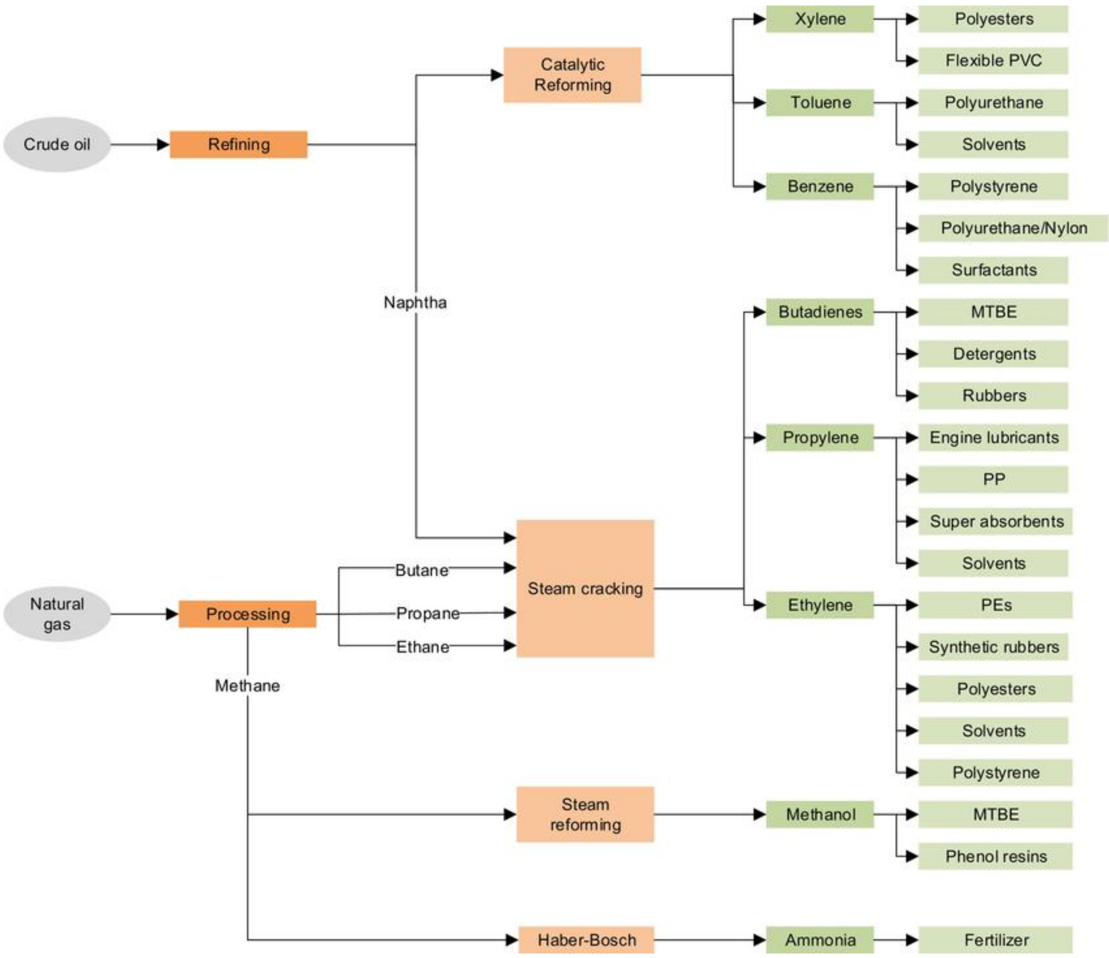


**Figure 5.7 – Renewable and non-fossil carbon feedstocks in chemical value chains**
*Source: WP2 Strategy, Chapter 5, original PDF*

This figure illustrates that renewable carbon integration requires systemic alignment between renewable energy, hydrogen supply, recycling streams and industrial conversion technologies.

For WP2.1, the CZ–HU catalytic pilot must therefore be understood within this broader renewable carbon transition context [1].

## B. Process Efficiency and Atom Economy as Transitional Measures

Before full carbon substitution becomes feasible, efficiency improvements and process optimisation remain essential.

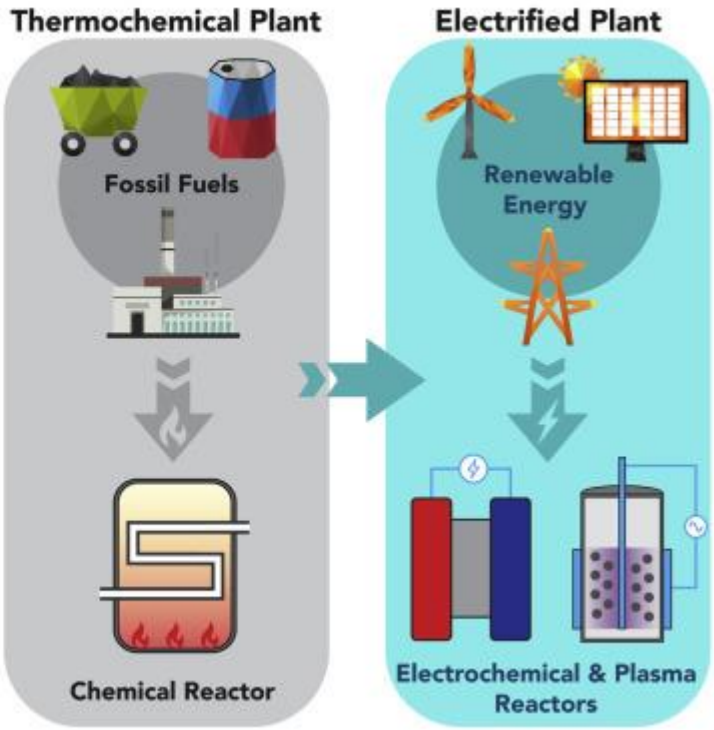


**Figure 5.8 – Process efficiency and atom economy as baseline decarbonisation measures**
*Source: WP2 Strategy, Chapter 5, original PDF*

This diagram positions process intensification and atom economy as foundational layers of decarbonisation. For WP2.1, catalytic optimisation and electrification of reaction steps directly support this baseline transition and align with EU ETS-driven industrial modernisation [3].

## C. Circular Carbon Through Material Recycling

Carbon circularity extends beyond $CO_2$ capture and includes material retention and chemical recycling.

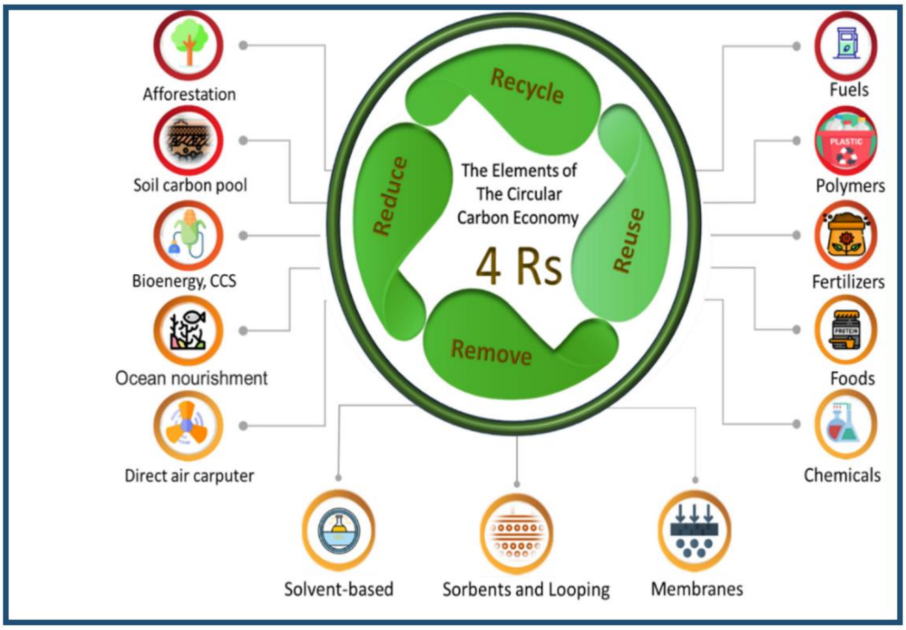


**Figure 5.9 – Circular use of carbon through material recycling and reuse**
*Source: WP2 Strategy, Chapter 5, original PDF*

The figure demonstrates that recycling efficiency reduces future $CO_2$ capture demand. For WP2, this confirms the structural linkage with WP1 and reinforces the necessity of integrated carbon management rather than isolated CCU deployment [1].

## D. $CO_2$ Utilisation Pathways in the Chemical Industry

$CO_2$ valorisation into fuels and intermediates represents one of the most technologically dynamic fields.

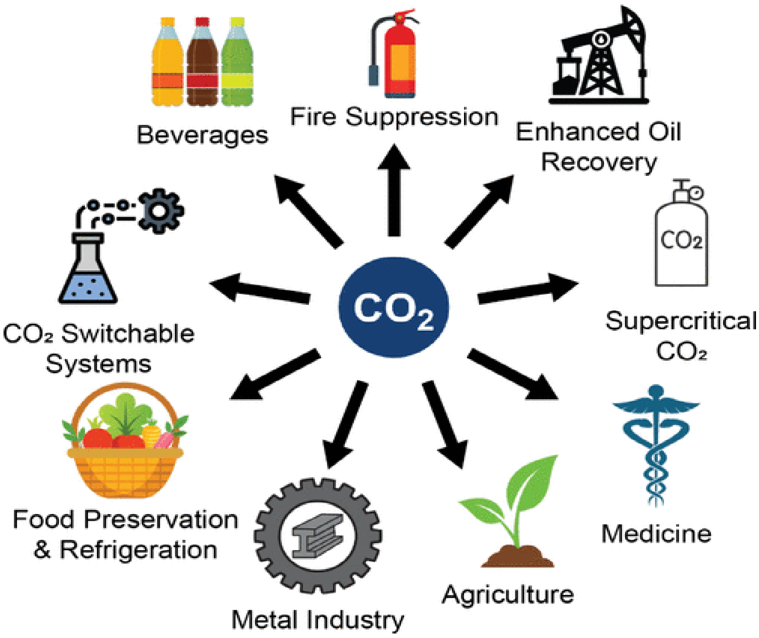


**Figure 5.10 – Conceptual pathways for $CO_2$ utilisation in the chemical industry**
*Source: WP2 Strategy, Chapter 5, original PDF*

The diagram outlines methanol synthesis, synthetic fuels and chemical intermediates as potential routes. For WP2.1, priority lies not in product breadth but in TRL advancement of selected catalytic pathways, particularly under renewable hydrogen constraints [2, 4].

## E. Integration of Material Circularity and Carbon Management

System-level coherence between recycling, carbon capture and renewable feedstocks is critical.

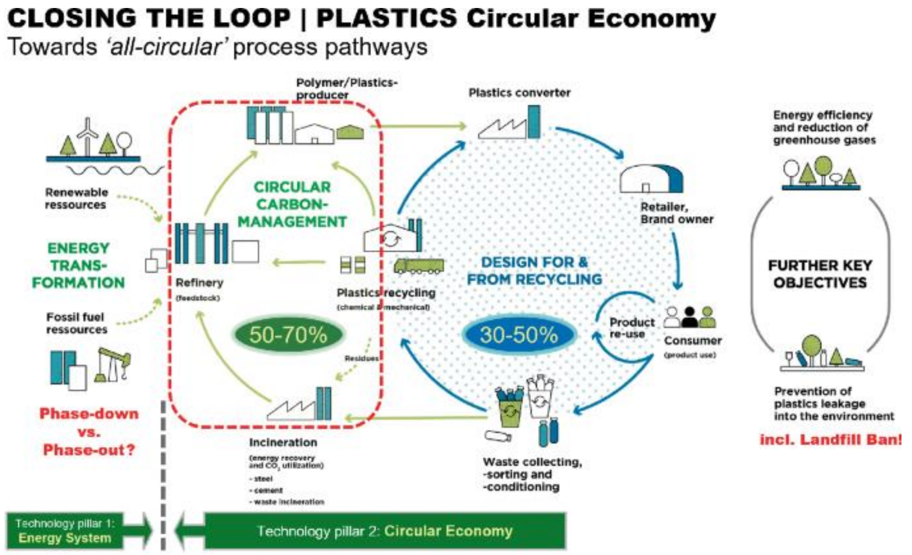


**Figure 5.11 – Strategic linkage between material circularity and carbon dioxide management**

*Source: WP2 Strategy, Chapter 5, original PDF*

This figure confirms that material circularity directly reduces structural $CO_2$ generation. WP2 must therefore operate within the GreenChemForCE network architecture, not as a standalone technological pillar.

## F. Process Intensification and Innovation Scaling

Long-term decarbonisation depends on accelerating technology readiness progression.

The figure below highlights innovation scaling and cross-WP technological integration. For WP2.1, cross-border collaboration (CZ–HU pilot) must function as a TRL acceleration platform rather than an isolated demonstration project.

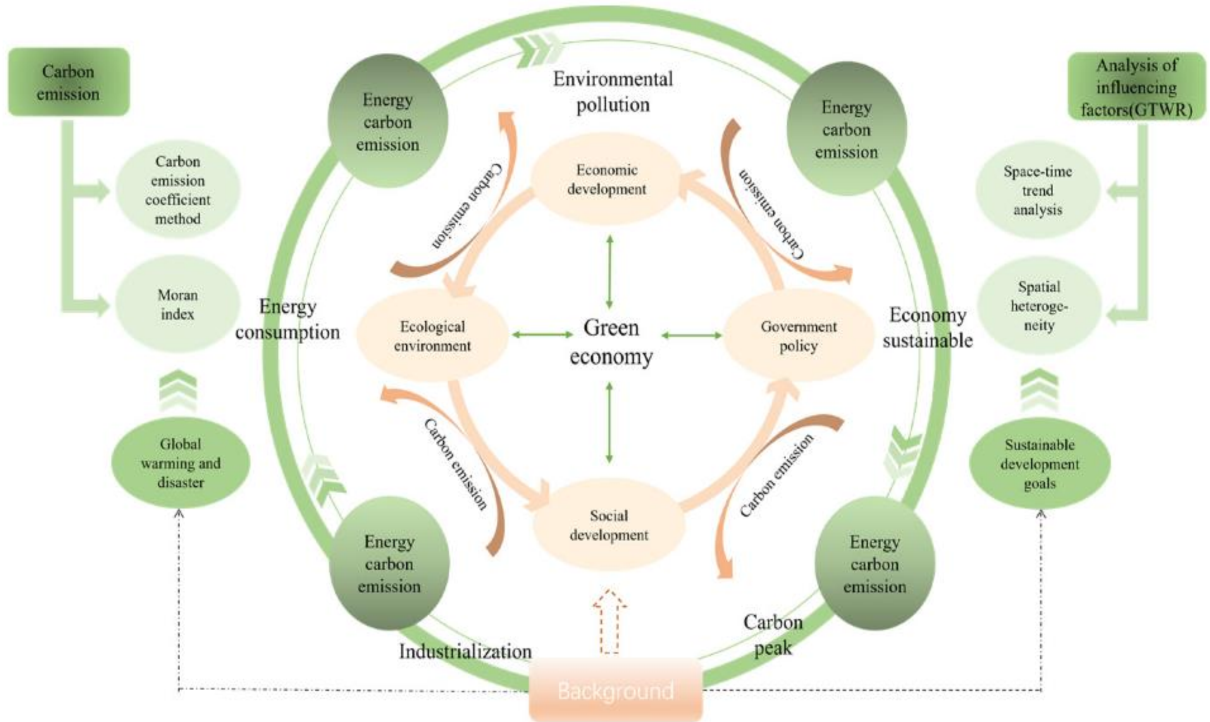


**Figure 5.12 – Contribution of process efficiency and atom economy (WP3) to WP2 carbon management objectives**

*Source: WP2 Strategy, Chapter 5, original PDF*

## References (Appendix 1)

[1] European Commission (2024). Communication on Industrial Carbon Management. Brussels.

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