



More Than Electrons

Scaling Up the Renewable Molecules of the Future

By: Zohre Kurt (Zuzi), PhD
Professor of Life Sciences and Renewable Energy

Preface

This book accompanies my inauguration as Professor of Life Sciences and Renewable Energy. It reflects the questions that have shaped my work and the direction I hope to pursue with students, colleagues and partners. The Northern Netherlands provides a meaningful setting for that work: its agricultural resources, industrial clusters, ports, energy infrastructure, renewable-electricity potential, and growing expertise in hydrogen and carbon management create opportunities to bring research closer to practice. My ambition is not to present one technology as the answer, but to help build the knowledge, partnerships, and experimental environments needed to make responsible choices.

The questions raised in this book extend beyond any single discipline or institution. Answering them requires scientists, engineers, policymakers, companies, operators, educators, and students to learn from one another. It also requires places where ideas can progress from models and laboratory experiments towards realistic demonstration—and where experience from practice can shape new research.

Like the journey behind it, this work was not created alone. I am deeply grateful to my colleagues for welcoming me, challenging my ideas, and helping me find my place within a new academic and regional community. I would especially like to thank Marten van der Laan for reviewing the manuscript with such care. His thoughtful questions encouraged me to explain what a technology does and why it matters and how it can be understood by readers outside my field. His contribution made this book clearer, more grounded, and more accessible. I also would like to thank Wim Elving and Carlos Donado for their careful editing and constructive suggestions. I cannot conclude without mentioning Daisy Tempelman, who supported me generously by sharing her professional expertise and reviewing my claims from a legal perspective.

I begin this chapter of my career with gratitude, curiosity, and a strong sense of purpose. The transition ahead will demand knowledge, honest assessment, creativity, cooperation, and the courage to connect ideas that have too often been considered separately.

The future will need more than electrons. It will need renewable molecules—and people willing to develop them responsibly, examine them critically, and build the systems that allow them to serve society. This book is my contribution to that conversation and an invitation to continue it together.



Table of Contents

Preface	3
1. From Energy Transition to Renewable Carbon	11
1.1 The Renewable Carbon Era	11
1.2 Bioenergy and the Renewable Carbon Imperative	13
2. Biogas for a Resilient Netherlands	17
2.1 The Strategic Role of Anaerobic Digestion	17
2.2 From Efficiency to Resilience	18
2.3 Anaerobic Digestion as Circular Energy Infrastructure	18
2.4 Lessons from Dutch Practice	19
2.5 How Digesters Strengthen Energy Resilience	20
2.6 Policy, Economics, and the Importance of RED III	21
2.7 Technology Is Advancing, but Regulation Must Keep Up	22
2.8 The Great Enabler: Cohesive Regulation Paves the Road for Innovation	23
2.9 Research and Innovation Priorities	24
2.10 What The Government Should Do	25
2.11 From Niche Technology to Resilient Infrastructure	27
3. Beyond Biogas	31
3.1 Biological Methanation and Renewable Methane	31
3.2 Is Methane the Final Product?	34
3.3 Power-to-Methanol: A Bridge Between Energy and Carbon	34
3.4 The Promise and Limitations of Renewable Methanol	36
3.5 Towards a Direct Biogas-to-Methanol Conversion	37
3.6 A Vision for Future Biogas Technologies	39

4. Adding Value to Carbon	41
4.1 Carbon Capture and Utilisation	41
4.2 Why CCU Matters in the Energy Transition	42
4.3 The EU Vision: From Carbon Management to Carbon Markets	43
4.4 From CO ₂ Waste to Industrial Feedstock	44
4.5 From Laboratory Promise to Practice	45
4.6 When Carbon Should Be Used—or Stored	47
4.7 The Main Challenge: Integration	50
4.8 The Transition to Renewable Carbon	50
4.9 Why the Northern Netherlands Matters	52
5. Beyond Energy	57
5.1 Recovering the Resources We Already Have	57
5.2 Renewable Molecules from Residual Streams	59
5.3 Microalgae as a Potential Biological Pathway	61
5.4 Beyond Energy, Towards Resource Circulation	63
6. The Professorship: Scaling Up the Renewable Molecules of the Future	67
6.1 From Upscaling Bioenergy to Building Renewable-Molecule Systems	67
6.2 A Research Cycle for Responsible Scale-Up	68
6.3 REMO as an Experimental Bridge	69
6.4 The Region as Part of the Research Environment	70
6.5 Bridging the Gap Between Discovery and Practice	70
6.6 People Are Part of the Infrastructure	71
6.7 Beyond the Label of Upscaling Bioenergy	72
6.8 A Personal Beginning	72
References	75
Reader's Guide	83
Glossary of Renewable Molecules	83
How to Use This Glossary	83
Afterword	89
About the Author	92



1. From Energy Transition to Renewable Carbon

1.1 The Renewable Carbon Era

Every generation faces a challenge that changes the direction of science and engineering. During the Industrial Revolution, the challenge was how to harness energy to power factories and transport people across growing nations. In the twentieth century, the focus shifted toward increasing productivity, improving industrial efficiency, and making energy available to an ever-expanding global population. Today, however, we face a different challenge, one that is perhaps more complex than any before it.

How can we continue to improve human well-being while reducing our dependence on finite fossil resources and limiting the environmental impacts of modern society?

This question lies at the heart of the global energy transition. Around the world, governments, industries, and researchers are searching for technologies that can provide reliable, affordable, and sustainable energy while dramatically reducing greenhouse gas emissions. In Europe, this ambition has been translated into policy and law through the European Green Deal (European Commission, 2019), the European Climate Law (Regulation (EU) 2021/1119, 2021), the REPowerEU Plan (European Commission, 2022), and the revised Renewable Energy Directive (European Parliament & Council of the European Union, 2023). Together, these initiatives establish an ambitious roadmap toward climate neutrality by 2050 while strengthening Europe's energy security and industrial competitiveness.

For many people, the energy transition is represented by wind turbines or solar panels. These technologies have become symbols of renewable energy, and rightly so. They are transforming electricity generation across Europe. Yet the transition toward a sustainable society involves much more than replacing one source of electricity with another.

Modern civilization depends on renewable electricity renewable heat, renewable fuels, renewable chemicals, and renewable materials. In other words, it depends on carbon. Carbon forms the backbone of transportation fuels, plastics, pharmaceuticals, fertilisers, construction materials, and countless products that shape our daily lives. Replacing fossil energy therefore requires us to rethink how we produce energy and how we obtain and manage carbon itself.

This realization marks an important shift in scientific thinking. Increasingly, researchers are moving beyond the concept of renewable energy toward the broader concept of *renewable carbon*. Rather than extracting carbon that has remained underground for millions of years, we are learning to recover, recycle, and continuously reuse carbon that already exists within our biological and industrial systems (European Commission, 2020). CO₂ is no longer viewed solely as a waste product. Organic residues are no longer regarded as materials to be discarded. Wastewater is no longer considered something to be treated before discharge. Instead, each of these streams contains resources that can be recovered and transformed into valuable products.

Throughout history, engineers have often designed systems with a single objective. Wastewater treatment plants were built to remove pollutants. Anaerobic digesters were constructed to stabilise organic waste. Power plants generated electricity. Fertiliser plants produced nutrients. Carbon capture systems prevented emissions. Each technology solved one problem exceptionally well.

The next generation of engineering must do more: recover energy while capturing carbon, treat wastewater while recovering nutrients, generate renewable fuels while producing valuable chemicals, and reduce greenhouse-gas emissions while strengthening regional economies. These technologies must function not in isolation, but as interconnected parts of a circular economy.

This philosophy has guided much of the research presented throughout this book. Rather than viewing biological, chemical, and electrochemical processes as competing technologies, the following chapters explore how they can complement one another. Biological systems efficiently convert complex organic matter into renewable gases. Catalytic processes transform these gases into platform chemicals and fuels. Electrochemical technologies recover nutrients and generate renewable hydrogen. Microalgae utilise recovered carbon and nutrients to produce biomass and high-value compounds. Together, these approaches create integrated resource recovery systems capable of addressing multiple societal challenges simultaneously.

The concept may appear ambitious, yet it reflects a broader transition taking place across Europe. Policies increasingly encourage industrial symbiosis, carbon circularity, renewable molecule production, resource efficiency, and renewable energy deployment (European Commission, 2019, 2020, 2022, n.d.-a; Directive (EU) 2023/2413, 2023; Regulation (EU) 2021/1119, 2021). The question is no longer whether these technologies will become important, but rather how they can be integrated to maximise environmental, economic, and societal benefits.

1.2 Bioenergy and the Renewable Carbon Imperative

A familiar saying in energy transition debates reminds us that major societal transitions do not occur because old resources disappear. They occur because better technologies, better systems, and better solutions emerge. Today, the world stands at another turning point in its history. Climate change, energy security, and the need for sustainable economic development are driving one of the largest transformations of the globe since the Industrial Revolution.

For more than a century, modern civilization has relied heavily on fossil fuels. Coal powered factories and railways during the Industrial Revolution, oil transformed transportation, and natural gas became a major source of heating and electricity generation. These fuels have enabled unprecedented technological progress, economic growth, and improvements in quality of life. Yet their widespread use has also come at a significant environmental cost. The combustion of fossil fuels releases large quantities of carbon dioxide (CO₂), the primary greenhouse gas responsible for anthropogenic climate change. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), limiting global warming to 1.5°C above pre-industrial levels requires rapid and sustained reductions in greenhouse gas emissions across every sector of society.

Europe has responded to this challenge with one of the world's most ambitious climate strategies. Through the European Green Deal (European Commission, 2019), the European Climate Law (Regulation (EU) 2021/1119, 2021), and the Fit for 55 legislative package (European Commission, n.d.-a), the European Union has committed itself to achieving climate neutrality by 2050 while reducing greenhouse gas emissions by at least 55% by 2030 compared with 1990 levels. These objectives are not environmental ambitions; they represent an economic and technological transformation that affects energy production, transportation, manufacturing, agriculture, waste management, and industrial processes.

At first glance, the solution might appear straightforward: renewable electricity to phase out fossil fuels. Solid proof of this argument lies in the success of wind and solar energy, which are success stories in this narrative, being among the fastest-growing renewable energy technologies worldwide, accompanied by dramatic cost reductions over the past two decades. However, as energy systems become increasingly complex, an important question emerges. Can renewable electricity alone meet society's growing energy needs?

1.2.1 Society's Energy Needs

Consider a winter evening in northern Europe. The sun has already set, electricity demand is high because millions of homes require heating, and a period of calm weather has reduced wind power generation. Hospitals continue operating, factories continue manufacturing products, food must still be transported across the continent, and airplanes continue flying. Some industrial processes require temperatures exceeding 1000°C, while the chemical industry depends on energy and also on carbon-containing raw materials to manufacture plastics, pharmaceuticals, and fertilisers.



These examples illustrate an important reality: the energy transition is about far more than replacing electricity generation. Society also requires renewable sources of heat, transport fuels, industrial feedstocks, and carbon-based molecules. Some sectors, often referred to as hard-to-abate sectors, cannot easily be electrified using current technologies. Heavy industry, aviation, maritime transport, and chemical manufacturing all require energy carriers that possess high energy density, can be stored over long periods, and can be transported efficiently.

This is where bioenergy enters the discussion.

Among all renewable resources currently available, biomass represents the largest source of renewable carbon on Earth. Yet biomass is also a limited resource. Forests cannot be harvested indefinitely without affecting biodiversity. Agricultural land must continue producing food. Organic wastes vary in quantity and quality. Consequently, the challenge is not to use more biomass, but to use available biomass as efficiently, strategically, and sustainably as possible. This concept lies at the heart of Europe's emerging circular bioeconomy, in which biological resources are repeatedly recovered, recycled, and transformed into high-value products before ultimately being converted into energy.

The transition from fossil resources to renewable carbon begins with large-scale infrastructure, and with the intelligent use of local resources. One of those technologies is anaerobic digestion since it connects energy production with waste management, nutrient recovery, and regional circularity. This makes it especially relevant for the Netherlands, where intensive agriculture, dense urban settlements, ambitious climate targets, and concerns about energy security all converge. The next chapter therefore turns to biogas as a practical and strategic example of renewable carbon in action, exploring how anaerobic digestion can support decentralized energy production and contribute to a more resilient Dutch energy system.



2. Biogas for a Resilient Netherlands

2.1 The Strategic Role of Anaerobic Digestion

The previous chapter introduced renewable carbon as a broader way of thinking about the energy transition: a shift from fossil fuels to renewable electricity, and a redesign of how society manages carbon, waste, and resources. Biogas brings this idea into a concrete national context. In the Netherlands, where agriculture, households, industry, wastewater treatment, and energy infrastructure are closely interconnected, anaerobic digestion offers a practical example of renewable carbon in action.

The Dutch energy transition is often discussed in terms of wind turbines, solar panels, hydrogen infrastructure, electrification, and grid expansion. These are essential parts of the transition, but they do not fully answer one of the most urgent questions facing the country: how can a renewable energy system remain reliable when the wind does not blow, the sun does not shine, the grid is congested, and imported energy becomes uncertain or expensive?

This question has become increasingly important. The Netherlands has made significant progress in scaling renewable electricity, especially wind and solar power, yet the energy system remains exposed to intermittency, grid congestion, and dependence on imported energy carriers. At the same time, gas extraction from the Groningen field was ended after extraction-induced earthquakes caused serious damage and social disruption. This necessary decision also removed a major domestic source of flexible energy, making the energy-security challenge more complex. IEA Bioenergy (2024) notes that natural gas has historically played a dominant role in the Dutch energy system, while import dependency has increased as domestic gas production has declined.

This chapter argues that anaerobic digestion, together with the biogas and biomethane it produces, should be understood as part of the Netherlands' strategic energy-resilience infrastructure. Anaerobic digestion is not only a waste-treatment technology. It is a way to convert manure, agricultural residues, food waste, wastewater sludge, and other organic materials into renewable energy, recovered nutrients, and useful fertiliser products. Biogas can be used for electricity and heat, upgraded to biomethane for injection into the gas grid, or integrated into future pathways involving hydrogen, methanation, and CO₂ utilisation.

The central argument of this chapter is simple: a resilient Dutch energy system will need more than electricity from wind and solar. It will also need local, storable, dispatchable, and circular energy carriers. Biogas is one of the few renewable options that can provide all four.

2.2 From Efficiency to Resilience

For decades, the Dutch energy system was shaped by efficiency, centralization, and integration into wider European energy markets. This model delivered reliable and affordable energy for much of the post-war period. However, recent shocks have revealed its weaknesses. Geopolitical instability, volatile energy prices, grid congestion, declining domestic natural gas production, and the rapid growth of variable renewable electricity have created a new policy framework.

In this context, resilience becomes as important as efficiency. Energy resilience means the ability of the system to withstand shocks, maintain essential services, recover from disruption, and adapt to changing circumstances. A resilient energy system is one that can continue functioning under stress.

This distinction matters because renewable electricity systems behave differently from fossil-based systems. Wind and solar energy are essential for decarbonisation, but they are variable. Their output changes with weather conditions, seasons, and time of day. Periods of low wind and solar generation, often referred to as *dunkelflaute*, can create the need for backup capacity.

Anaerobic digestion can help address this problem. Unlike wind and solar electricity, like hydrogen, biogas can be stored and converted when needed. Research on flexible and demand-driven biogas production shows that biogas plants can help balance renewable electricity systems when feeding strategies, gas storage, and control systems are designed for flexibility rather than constant baseload operation (Dittmer et al., 2022; Dotzauer et al., 2019; Mauky et al., 2017).

Anaerobic digesters are already distributed across farms and other local sites. This decentralized infrastructure spreads energy production among farms, municipalities, industrial sites, wastewater-treatment plants, and regional energy hubs rather than concentrating it in a few large facilities. The result is greater redundancy, more local control, and a closer connection between energy production and regional resource flows.

2.3 Anaerobic Digestion as Circular Energy Infrastructure

Anaerobic digestion is a biological process in which microorganisms break down organic material in the absence of oxygen. The process produces two main outputs: biogas and digestate. Biogas consists mainly of methane and CO₂, while digestate is a nutrient-rich residual material that can potentially be used as fertiliser, depending on its composition and regulatory classification (Aworanti et al., 2023).

This dual output is what makes anaerobic digestion so valuable. It is both an energy technology and a circular-economy technology. It is one of the clearest examples of the shift from eliminating waste to recovering value.

Biogas can be used in several ways. It can be burned in combined heat and power units to produce electricity and heat. It can be upgraded by removing CO₂ and impurities to produce biomethane, also known as green gas. This biomethane can be injected into the existing gas grid or used in transport, industry, or heating. In more advanced systems, the CO₂ fraction of biogas can be combined with hydrogen to produce additional methane through biological or chemical methanation (Aieamsam-Aung et al., 2023).

The Netherlands is well suited to anaerobic digestion because its agricultural sector produces substantial manure and organic-residue streams, its extensive gas infrastructure can support biomethane, and growing electricity-grid constraints increase the value of flexible energy carriers.

IEA Bioenergy (2024) highlights that biomass plays a significant role in Dutch renewable energy consumption and that biogas differs from several other bioenergy streams because it can be produced from domestic resources rather than imported fuels. This domestic character is important. From the perspective of resilience, local availability is not a minor advantage. It is a strategic feature.

2.4 Lessons from Dutch Practice

Dutch experience with anaerobic digestion shows both promise and difficulty. The technology works, but its success depends strongly on feedstock choice, subsidy design, digestate management, permitting, and market conditions.

Further relevant cases come from the Northern Netherlands. Achinas et al. (2019) examined a biogas-based combined heat and power installation using cow manure, grass straw, and sugar beet pulp. The economic outcomes varied substantially by feedstock: cow manure and sugar beet pulp resulted in negative net present values, whereas grass straw produced a positive net present value even without subsidies. Complementary work by Pierie et al. (2015, 2016) evaluated anaerobic-digestion and biomethane-production pathways from an energy-system and environmental perspective. Their analyses showed that the sustainability of biogas depends strongly on feedstock selection, transport distance, process configuration, and the internal use of the energy produced. Locally available waste streams generally performed better than dedicated energy crops, while using part of the biogas internally for process heat and electricity substantially improved energy efficiency and environmental performance.

Together, these studies demonstrate that the viability of anaerobic digestion cannot be determined solely by biogas yield: economic performance, feedstock origin, logistics, process integration, and environmental impacts must all be considered.

These findings matter because they show that anaerobic digestion cannot be judged as a single uniform technology. A digester using manure, a plant using food-processing residues, a wastewater-based system, and an industrial biomethane installation all have different economics and regulatory conditions. The performance of a biogas project depends on the specific local system in which it is embedded.

At the industrial scale, Dutch companies are already developing relevant technological capabilities. Bright Renewables offers membrane-based biogas upgrading systems with modular capacities and methane recovery of at least 99.5% in its PurePac product range. HoSt Group also supplies membrane-based upgrading systems designed for biomethane production, grid injection, bio-CNG, bio-LNG, and bio-CO₂ applications (Bright Renewables, n.d.; HoSt Group, n.d.). These examples show that the Netherlands has industrial knowledge and technology providers that can support the further development of decentralized and semi-decentralized biomethane infrastructure.

2.5 How Digesters Strengthen Energy Resilience

Anaerobic digesters contribute to energy resilience in several ways.

Digesters enable local energy production. Organic residues from farms, food-processing companies, municipalities, and wastewater-treatment facilities can be converted into energy within the same region. This reduces dependence on imported fossil fuels, creates value from locally available resources, and strengthens regional energy self-sufficiency.

They can also provide flexibility. Because biogas can be stored, its conversion into electricity or heat can be shifted to periods of high demand or low wind and solar generation. Flexible feeding, model-predictive control, and gas storage can improve the ability of biogas installations to respond to changing demand patterns (Dittmer et al., 2022; Dotzauer et al., 2019; Mauky et al., 2017).

This function is also recognised in the Dutch Integrated Infrastructure Outlook 2030–2050, known as II3050. The scenarios investigated in II3050 demonstrate that a climate-neutral energy system requires substantial short-term and seasonal flexibility and a continuing role for storable gaseous energy carriers. Hydrogen has a central role in all the scenarios, partly because the sustainable availability of biomass limits the potential contribution of green gas. Nevertheless, II3050 also identifies a need for methane and hydrogen storage and recognises that renewable gases can complement electricity, particularly during periods of high seasonal demand (Netbeheer Nederland, 2023). The subsequent Netbeheer Nederland Scenarios, 2025 Edition builds on II3050 and introduces the Koersvaste Middenweg scenario as a central pathway based on current trends and policy ambitions. Although this configuration emphasizes rapid electrification and hydrogen, it also retains complementary energy carriers to balance supply and demand and reduce pressure on the electricity infrastructure (Netbeheer Nederland, 2025). Biomethane

produced by anaerobic digestion can contribute to this role because it is storable and, once upgraded to the required quality, can use parts of the existing gas infrastructure.

A distributed network of digesters also adds redundancy. It is less vulnerable to single-point failures than a system that depends entirely on a small number of centralized facilities or imported energy flows. Local digesters can supply farms, heat networks, industrial sites, and municipal energy systems. Their contribution may be modest nationally, but strategically valuable locally, particularly during supply disruptions or pressure on electricity infrastructure.

Anaerobic digestion can reduce greenhouse-gas emissions by capturing methane that might otherwise escape during the storage or decomposition of organic wastes and by replacing fossil gas, heat, or electricity. The actual climate benefit depends on feedstock selection, methane-leakage control, digestate management, transport distances, and the fossil energy source displaced.

Anaerobic digestion can also support the reduction of ammonia emissions, but this benefit is not produced by digestion alone. Digestion converts part of the organic nitrogen into ammonium, which increases the fertiliser value of digestate but may also increase the risk of ammonia volatilization during storage and field application. Ammonia emissions can be reduced when digestion is combined with measures such as covered digestate storage, acidification, ammonia stripping or recovery, and rapid incorporation or low-emission injection into the soil. Consequently, the climate and air-quality performance of a digester should be evaluated across the complete manure and digestate-management chain rather than at the reactor alone (Aguirre-Villegas et al., 2019; Lemes et al., 2023; Morey et al., 2023).

In a resilient renewable-energy system, these combined characteristics become increasingly valuable. A digester is therefore more than a machine for producing gas: it is a controllable local energy source, a form of distributed storage, a waste-treatment facility, and a nutrient-management tool. By connecting these functions, anaerobic digestion can improve a region's capacity to absorb fluctuations, respond to supply disruptions, and recover from stresses affecting the wider energy system.

2.6 Policy, Economics, and the Importance of RED III

One important case is the Green Power biogas plant analysed by Wageningen University & Research. Gebrezgabher et al. (2010) assessed the economic performance of anaerobic digestion using net present value and internal rate of return. They found that most scenarios were economically positive when subsidies were included, while the no-subsidy scenario was not financially viable. The study also showed that feedstock optimisation, digestate treatment, and the regulatory treatment of reverse-osmosis products were central to economic performance.

The economics of anaerobic digestion remain challenging. High upfront investment costs, uncertain energy prices, feedstock competition, digestate regulations, and grid-connection limitations all influence project viability. Dutch studies show that profitability is closely linked to policy support, feedstock selection, and the value assigned to digestate and energy outputs (Achinas et al., 2019; Gebrezgabher et al., 2010).

This is where policy becomes decisive. The SDE++ scheme, a Dutch government operating subsidy that covers the financial gap between the cost of sustainable technologies and the market value of energy, remains one of the most important Dutch instruments for supporting renewable energy and climate-transition projects. For biomass-based electricity, heat, combined heat and power, and green gas production, the Netherlands Enterprise Agency states that projects may need to demonstrate compliance with Renewable Energy Directive sustainability criteria depending on the installation type, feedstock, project date, and applicable thresholds (Netherlands Enterprise Agency, 2026a, 2026b).

At the European level, the revised Renewable Energy Directive (RED III) significantly increases the relevance of biogas and biomethane. Directive (EU) 2023/2413 revised the European renewable energy framework and raised the EU's binding renewable-energy target for 2030 to at least 42.5%, with an ambition to reach 45% (Directive (EU) 2023/2413, 2023; European Commission, 2026).

This creates an opportunity for the Netherlands. RED III raises the EU's binding renewable-energy target for 2030 to at least 42.5% and strengthens the sustainability and greenhouse-gas-saving requirements applied to bioenergy. Waste- and residue-based biogas fits this direction because it produces renewable energy from existing streams—such as animal manure, sewage sludge, separately collected biowaste, agricultural residues, and food-processing residues—without creating the same pressure on agricultural land as dedicated energy crops. Several of these streams appear in Annex IX of the directive, giving eligible advanced biofuels and biogas additional relevance to its transport obligations. Biogas can serve several sectors through electricity and heat, while upgraded biomethane can replace fossil natural gas where direct electrification is difficult. Manure-based pathways can achieve especially high lifecycle greenhouse-gas savings because controlled digestion captures methane that might otherwise escape; RED III's methodology explicitly recognises this benefit through a credit for improved manure management. These advantages nevertheless depend on low methane leakage, covered digestate storage, efficient biogas use, and responsible digestate management. Waste- and residue-based systems therefore fit RED III because biogas is renewable and because those systems can unite renewable-energy production, waste treatment, avoided methane emissions, and the circular use of local resources (European Parliament & Council of the European Union, 2023).

However, RED III also increases the administrative burden on producers. Sustainability documentation, traceability, greenhouse gas accounting, and certification requirements are becoming more important. For large professional operators, this may be manageable. For smaller farmers, cooperatives, and local initiatives, it can become a barrier.

2.7 Technology Is Advancing, but Regulation Must Keep Up

Technological development is improving the performance of anaerobic digestion. Advanced upgrading systems can produce grid-quality biomethane. Digital control systems can support demand-driven operation. Feedstock pre-treatment and co-digestion can improve methane yields. CO₂ from upgrading can potentially be captured, liquefied, reused, or converted with hydrogen into additional methane.

Reviews of anaerobic digestion technologies show that pre-treatment, co-digestion, process intensification, microbial regulation, and modelling can improve biogas and biomethane production (Aworanti et al., 2023). Research on hydrogen and methane production from organic waste also shows that biological pathways, such as sequential hydrogen and methane production, may become relevant in future integrated bioenergy systems (Rawoof et al., 2021).

Hydrogen integration is particularly interesting. Hydrogen can be combined with the CO₂ fraction in biogas through methanation, increasing methane output and creating a way to store renewable hydrogen in the form of methane. Research on CO₂ hydrogenation for biogas upgrading identifies this route as promising, although feasibility depends on catalyst performance, hydrogen availability, system integration, and economics (Aieamsam-Aung et al., 2023).

These developments suggest that the digester of the future may look different from the digester of the past. It may operate flexibly, integrate with solar or wind power, use digital control, upgrade gas to biomethane, capture CO₂, produce biofertiliser, and interact with hydrogen systems. Yet this raises a critical question: are operators legally, economically and administratively able to make these changes?

2.8 The Great Enabler: Cohesive Regulation Paves the Road for Innovation

While we have highlighted the importance of finance and technology for the successful development of resilience-oriented innovation in anaerobic digestion, a third crucial element becomes necessary. It is regulation.

Digester operators in the Netherlands do not operate under a single simple policy framework. They are simultaneously energy producers, waste processors, manure handlers, fertiliser producers, environmental-permit holders, grid-connected gas or electricity suppliers, and subsidy recipients. Each role comes with different legal, administrative, and certification requirements.

This creates a fragmented compliance landscape. Operators may need to consider RED sustainability criteria, SDE++ rules, manure legislation, waste regulations, digestate classification, fertiliser rules, environmental permits, grid-injection requirements, and transport documentation. RVO states that biomass-based installations receiving SDE++ support may need to demonstrate compliance with RED sustainability criteria (Netherlands Enterprise Agency, 2026a). Business.gov.nl also notes that Dutch businesses handling manure, sewage sludge, compost, waste transport, and fertiliser use face multiple registration, reporting, and compliance obligations (Business.gov.nl, 2024, n.d.).

This complexity becomes especially problematic when an operator wants to innovate. A technically sensible modification, such as changing a feedstock mix, adding pre-treatment, introducing flexible feeding, upgrading gas to biomethane, capturing CO₂, using hydrogen for methanation, or producing a new digestate-derived fertiliser product, may trigger new permit reviews, certification checks, sustainability documentation, grid approval, or waste-status reassessment.

The Dutch Environment and Planning Act, which entered into force on 1 January 2024, combines and modernizes rules related to spatial planning, housing, infrastructure, environment, nature, and water (Informatiepunt Leefomgeving, 2024). In practice, however, operators still need to navigate permitting through the Omgevingsloket and deal with different authorities and compliance requirements.

Digestate regulation is especially important. Dutch manure policy has historically treated digestate differently depending on the composition of the input material and whether co-substrates (mixtures) are permitted. In co-digestion, digestate may be treated as fertiliser or waste depending on whether specific conditions are met, including the share of manure and whether added materials appear on permitted lists. This directly affects disposal costs, marketability, and operational flexibility (Business.gov.nl, 2024; Hermann et al., 2019).

As a result, regulation has either the potential to purposefully enable or unintentionally discourage experimentation. Operators may avoid testing new feedstocks, nutrient-recovery technologies, flexible operating strategies, or upgrading systems because the administrative risk is too high. This is a serious problem for energy resilience. If digesters are expected to help during *dunkelflaute*, integrate with hydrogen systems, support circular nutrient recovery, and provide flexible local backup, then operators need permission to adapt.

A rigid regulatory framework locks plants into existing operating models. A resilience-oriented framework should allow controlled experimentation, safe modification, and faster approval of improvements.

2.9 Research and Innovation Priorities

The future of biogas in the Netherlands depends on several research and innovation priorities. One priority is to maximise methane production from biogenic material through better feedstock management, process control, microbial performance, pretreatment, co-digestion, and modelling. Reviews show that these factors directly influence methane yield, process stability, and overall biogas performance (Aworanti et al., 2023).

Hydrogen integration is another priority. Hydrogen can be combined with the CO₂ in biogas to produce more methane, improving methane yield and creating a storage pathway for renewable hydrogen. Research on CO₂ hydrogenation shows technical promise, although further development and economic evaluation are still needed (Aieamsam-Aung et al., 2023).

Research should also explore whether existing biogas infrastructure can support future hydrogen systems. If hydrogen becomes a dominant energy vector, feedstocks now used for biogas may also become relevant for biological or chemical hydrogen production. Reviews of sequential hydrogen and methane production show that organic wastes can support both products, with yields shaped by pH, temperature, substrate composition, retention time, nutrient balance, and process configuration (Rawoof et al., 2021).

Flexibility completes this research agenda. Research on flexible biogas production distinguishes among ramping speed, power range, and duration. Short-term flexibility is often determined by the response of the combined heat and power unit, whereas longer-term flexibility depends more strongly on gas-storage capacity, operating strategy, and the ability to modulate biological gas production (Dotzauer et al., 2019). These capabilities matter for resilience because the Netherlands will need backup for both daily fluctuations and longer periods of low wind and solar generation. Future research should therefore examine how digesters can adjust production, store gas, switch among electricity, heat, and biomethane, and coordinate with local demand for electricity, heat, methane, and hydrogen.

2.10 What The Government Should Do

If anaerobic digestion is to become a serious component of the Dutch energy transition, government policy must look beyond general support for renewable energy production. Biogas and biomethane should not only be viewed as outputs of waste treatment and manure management but also as strategic resources that contribute to energy resilience. Government's role is to establish targets, incentives, infrastructure rules, environmental safeguards, and market conditions that enable farmers, water authorities, municipalities, cooperatives, and industrial operators to develop and operate anaerobic-digestion systems effectively. Within such a framework, these systems can provide locally produced energy, strengthen rural economies, capture methane that might otherwise escape from manure and organic wastes, and supply a storable renewable gas that complements variable renewable energy sources such as wind and solar power.

Policy recognition and consistency are essential. Biogas and biomethane should have a clearly defined place in national energy planning alongside electricity, hydrogen, heat, and energy infrastructure. They should be considered in decisions concerning grid congestion, seasonal energy security, rural development, agricultural transition, nutrient management, and the circular economy.

This recognition must also be reflected consistently across policy areas and regulatory frameworks. For example, the 2026 consultation draft of the *Regeling gemeentelijke instrumenten warmtetransitie* refers to buildings ceasing to use “methane gas” rather than specifically fossil natural gas. Because biomethane is chemically identical to natural gas and consists primarily of methane, such terminology may unintentionally create ambiguity regarding the future role of renewable gaseous fuels. Policies intended to phase out fossil energy use should therefore distinguish clearly between the fossil or renewable origin of a fuel and its molecular composition.

Recent Dutch legislation demonstrates that this distinction is both possible and necessary. The proposed *Wet bijmengverplichting groen gas* explicitly recognises green gas as a renewable energy carrier and introduces obligations for energy suppliers to increase the share of renewable gas supplied to consumers. In doing so, it acknowledges the role of renewable gas in achieving climate objectives, strengthening energy security, and reducing dependence on imported fossil fuels (Ministerie van Klimaat en Groene Groei, n.d.). Similarly, the *Energieregeling* provides a regulatory framework for renewable gases through provisions relating to sustainability requirements, guarantees of origin, certification, and market participation (Ministerie van Klimaat en Groene Groei, 2025).

Even if biomethane is ultimately prioritised for sectors with limited decarbonisation alternatives, such as certain industrial processes or high-temperature heat applications, policy should continue to differentiate between a fuel's origin, the infrastructure used to distribute it, and the chemical characteristics of the energy carrier itself. Failure to make these distinctions risks creating unnecessary barriers to the future use of renewable gases. For instance, infrastructure decisions that permanently remove local gas networks could also eliminate future opportunities for distributing biomethane and other renewable gaseous fuels, thereby reducing long-term flexibility and resilience within the Dutch energy system (Ministry of Housing and Spatial Planning, 2026).

Regulatory coordination is equally important. Digester operators currently face overlapping requirements concerning waste management, manure regulation, fertiliser use, environmental permits, RED certification, SDE++ eligibility, digestate classification, and gas-grid injection. These regulations serve important environmental and safety objectives, but fragmented procedures and inconsistent definitions can increase project risk, delay investment, and impede innovation. Operators require coordinated guidance, predictable decision-making timelines, and closer alignment among municipalities, provinces, water authorities, grid operators, and national agencies. A single point of regulatory coordination could help applicants understand which requirements apply and in what sequence, without compromising environmental standards.

Responsible innovation also requires a clearer regulatory pathway. Future anaerobic-digestion plants may incorporate new feedstocks, pretreatment systems, flexible feeding strategies, digestate-processing technologies, carbon dioxide capture, hydrogen integration, and biological or catalytic methanation. Existing regulations often assess these additions separately, even when they function as components of a single integrated system. Government should therefore establish an innovation pathway that allows pilot-scale and demonstration-scale testing under clearly defined safety, monitoring, emissions, and reporting conditions. Successful demonstrations could then provide evidence supporting permanent permits and wider deployment.

Digestate regulation deserves particular attention. Digestate is not a feedstock for anaerobic digestion but one of its principal outputs. Depending on the origin of the input materials and the treatment applied, however, it may continue to be legally classified as waste or manure even when it contains recoverable nitrogen, phosphorus, potassium, and organic matter. This classification can restrict processing, transport, marketing, and application, preventing valuable nutrients from reaching markets where they could replace mineral fertilisers.

The objective should not be to classify all digestate automatically as a fertiliser because its composition, pathogen content, contaminant levels, nutrient availability, and stability can vary considerably. Instead, government should establish transparent, quality-based pathways through which demonstrably safe and consistent digestate products can obtain fertiliser-product status or end-of-waste status. This would allow suitable materials to be recognised as secondary raw materials rather than wastes while maintaining controls on contaminants, nutrient losses, and inappropriate land application. Clear quality standards, certification procedures, and monitoring requirements would reduce disposal costs, encourage nutrient-recovery technologies, and strengthen domestic fertiliser resilience (Saveyn & Eder, 2014).

Flexible operation should also be supported, but its contribution must be described accurately. Anaerobic digestion is a biological process with comparatively slow dynamics and generally performs most reliably under continuous operating conditions. Although gas production can be adjusted to some degree through feeding strategies and process control, repeatedly accelerating or slowing biological activity is more constrained than controlling batteries, electrolyzers, or electric boilers. The primary source of flexibility therefore arises from separating relatively continuous biogas production from the timing of gas utilisation.

Small on-site gas-storage systems can shift electricity or heat production over periods of hours or days, while upgraded biomethane injected into the gas network and connected to larger storage facilities can contribute over much longer periods. Batteries are generally better suited to rapid response and short-duration electricity balancing. Electrolyzers and power-to-heat systems can absorb surplus electricity quickly and provide demand-side flexibility, while hydrogen combined with large-scale storage can address longer-duration imbalances. Biogas occupies a different position within the energy system. Its principal value lies in providing dispatchable renewable energy when electricity generation from wind and solar is limited rather than absorbing excess electricity during periods of abundance. Consequently, individual digesters should not be portrayed as seasonal storage technologies. Seasonal resilience emerges when continuously produced gas is upgraded, aggregated, injected into a gas network, or stored in infrastructure capable of holding substantially larger volumes (Dotzauer et al., 2019).

Policy support should reflect these distinct system functions. Support for on-site gas storage, larger or more flexible combined heat and power units, biomethane upgrading, demand-oriented operation, gas-grid injection, and participation in local energy hubs could enable biogas systems to provide short- and medium-duration flexibility services. Maintaining access to suitable gas infrastructure and strategic gas-storage capacity is likely to be more important for their contribution to long-term and seasonal resilience. Policies should therefore reward not only the volume of gas produced but also verifiable system services such as dispatchable generation, peak-demand support, avoided methane emissions, and the availability of renewable gas during prolonged periods of low wind and solar generation.

Regulatory sandboxes could further support resilience-oriented biogas innovation by allowing selected farms, cooperatives, municipalities, water authorities, and industrial operators to test integrated operating models under clearly defined safety, environmental, and reporting requirements. Demonstration projects might combine flexible CHP operation, biomethane injection,



temporary gas storage, carbon dioxide capture, hydrogen-assisted methanation, and standardised fertiliser products derived from digestate. Their purpose would be to generate evidence for updating regulations originally designed around conventional, single-purpose installations, rather than to weaken environmental protection.

In summary, the Netherlands requires a coherent policy framework that identifies where anaerobic digestion creates the greatest public value. Through consistent terminology, coordinated regulation, quality-based recognition of digestate products, maintenance of suitable gas infrastructure, and controlled opportunities for innovation and experimentation, anaerobic digestion can become an important component of a resilient, circular, and locally grounded energy system.

2.11 From Niche Technology to Resilient Infrastructure

Anaerobic digestion should not be viewed as a niche technology. It is a strategic infrastructure option that connects renewable energy production, manure and organic waste treatment, circular nutrient management, rural development, and energy-system resilience.

As the Netherlands moves toward an energy system with higher shares of wind and solar power, the need for flexible, local, reliable, and storable energy will increase. Biogas and biomethane can help meet this need because they are produced from domestic organic residues, can be stored more easily than electricity, and can be converted into heat, power, renewable gas, or future hydrogen-related energy carriers.

The evidence suggests that anaerobic digestion can contribute to a more resilient Dutch energy system. Flexible feeding, gas storage, model predictive control, upgrading technologies, CO₂ utilisation, and hydrogen integration all point toward a more advanced role for biogas in the future. But this future will not happen automatically.

The decisive enabler is regulation. Operators need the ability to change feedstocks, modify processes, upgrade equipment, test new business models, and develop new outputs without being trapped in administrative uncertainty. If every modification risks triggering complex reclassification, new certification, or long permitting delays, innovation will remain limited.

A resilient biogas sector therefore requires more than subsidies and technology. It requires predictable permitting, harmonized certification, clearer digestate rules, and safe regulatory space for experimentation. With the right policy framework, anaerobic digestion can become a core component of the Dutch energy future. It can help the Netherlands move from an energy system optimized mainly for efficiency toward one designed for resilience, security, circularity, and long-term sustainability.

In this sense, biogas is renewable carbon made practical, local, and resilient.



3. Beyond Biogas

3.1 Biological Methanation and Renewable Methane

The previous chapters argued that biogas is more than a renewable fuel. It is a local, storable, and flexible form of renewable carbon. Through anaerobic digestion, organic residues such as manure, food waste, agricultural by-products, and wastewater sludge can be transformed into a gas that supports energy resilience, nutrient recovery, and circular resource use. Yet once biogas has been produced, an important question remains: what is the best way to use it and how to valorise it?

For decades, the most common answer was relatively simple. Biogas could be combusted in combined heat and power systems to produce electricity and heat, or it could be upgraded into biomethane and injected into the gas grid. Both routes remain valuable. Combined heat and power can serve local energy demand, especially when heat can be used effectively on site. Biomethane, meanwhile, can replace fossil natural gas while making use of existing gas infrastructure. But the energy transition is changing the question. The challenge is no longer how to produce renewable energy. It is also how to direct renewable carbon toward the greatest possible value.

This question was central in our recent comparative study of decentralized biogas valorisation pathways. The study compared three routes: combined heat and power, conventional biogas upgrading, and biological methanation (where CO_2 of biogas is combined with hydrogen to make more methane with biological organisms) (Figure1). The analysis combined process-level energy efficiency with life cycle assessment, allowing the three pathways to be evaluated by how much useful energy they produce and by how their environmental burdens shift under different system boundaries (Alavi et al., n.d.).

The comparison showed that biological methanation can produce the highest absolute energy output because it converts the CO_2 fraction of biogas into additional methane. In this sense, biological methanation extends the value of biogas by using its methane fraction and its CO_2 fraction.

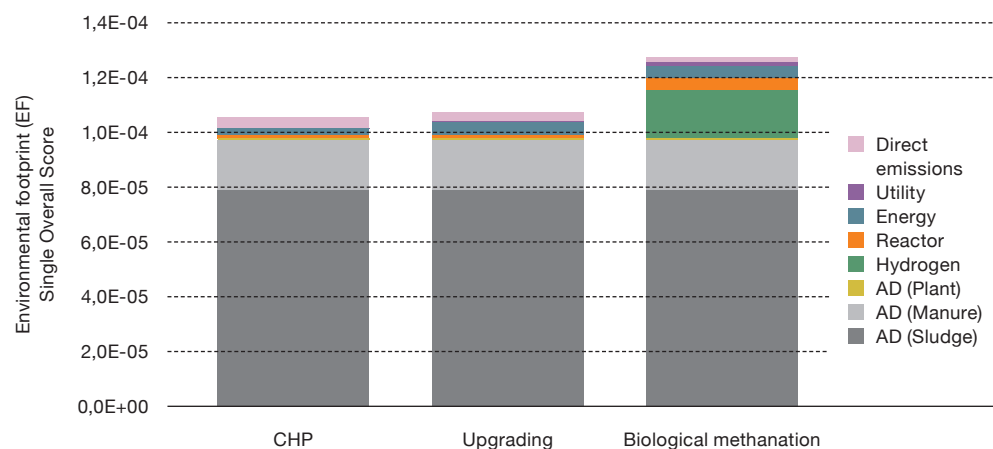


Figure 1 Comparison of environmental impact of biogas farm technologies (Adapted from Alavi et al., manuscript submitted for publication)

However, this benefit comes with an important limitation: biological methanation requires hydrogen. When hydrogen is produced through water electrolysis, the electricity demand becomes a major factor in the total energy and environmental performance of the pathway. This finding aligns with broader hydrogen-based conversion studies, which show that the sustainability of such processes depends strongly on the electricity source, electrolyser performance, and hydrogen supply chain (Alavi et al., n.d.; Pashchenko, 2024).

At the process level, biological methanation showed the highest environmental burden among the three pathways, mainly because of the material and electricity requirements associated with hydrogen production (Figure 1). In contrast, combined heat and power and conventional upgrading had lower direct process-level burdens. However, when avoided fossil natural gas was included in the assessment, the ranking changed (Figure 2). Biological methanation achieved the best net environmental performance because it produced the largest amount of biomethane and therefore displaced the greatest amount of fossil natural gas (Alavi et al., n.d.). Similar life cycle assessment studies have shown that biomethane-producing pathways can provide strong environmental benefits when they replace fossil fuels and when upstream methane leakage and digestate-related impacts are controlled (Lin et al., 2024; Patel et al., 2025).

This result reveals one of the central lessons: the answer depends on the boundary of the question. If the question is, “Which pathway has the lowest direct process burden?”, then conventional upgrading or combined heat and power may appear more favourable. If the question is, “Which pathway maximises renewable methane and fossil gas replacement?”, then biological methanation becomes more attractive (Figure 2). The value of the technology therefore depends on what the energy system needs, what the boundary of assessment includes, and whether low-carbon hydrogen is available.

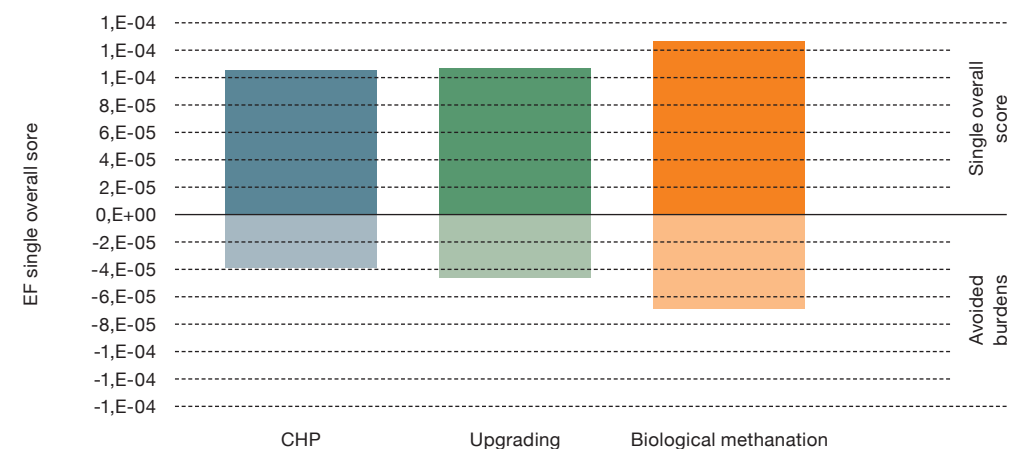


Figure 2 Biological methanation increases biomethane output by converting the CO₂ fraction of biogas into methane, but its performance depends strongly on low-carbon hydrogen availability and on how avoided fossil natural gas is included in the system boundary. (Adapted from Alavi et al., manuscript submitted for publication).

The same study also showed that digestate sludge management was especially important, influencing freshwater eutrophication, climate change, acidification, and other impact categories (Alavi et al., n.d.). This confirms an important message from the earlier chapters: resource recovery systems cannot be judged by their main product. A digester produces gas, but it also produces digestate. A methanation system produces methane, but it also depends on hydrogen. A methanol system produces a liquid chemical, but it also depends on electricity, carbon sources, catalysts, and purification steps. In circular systems, the side streams are never secondary. They shape the whole system.

By converting CO₂ and renewable hydrogen into methane, biological methanation offers a pathway for carbon utilisation and a way of introducing flexibility into energy systems increasingly dominated by intermittent renewable sources such as wind and solar power. As the availability of renewable electricity fluctuates, hydrogen production and subsequent methane synthesis will need to operate under dynamic rather than steady-state conditions. This represents a significant scientific and engineering challenge. While biomethanation has demonstrated promising performance at laboratory scale, its deployment in practical environments requires a deeper understanding of process stability, microbial resilience, gas-liquid mass transfer, and reactor performance under variable operating conditions. Addressing these challenges is essential for enabling the transition from controlled laboratory systems to robust and economically viable applications in agriculture and industry. Within the professorship, several research initiatives, including the recently awarded Interreg project Watts in Grass, contribute to this ambition by exploring biological methanation in integrated farm-scale energy systems.

3.2 Is Methane the Final Product?

Biological methanation raises a deeper question. “If we can convert CO₂ into additional methane, should methane be the final product? “Methane is valuable because it is energy dense, storable, and compatible with existing gas infrastructure. It can provide dispatchable renewable energy and help balance energy systems with high shares of wind and solar power. But methane is still mainly an energy carrier. In most applications, it is ultimately burned. In a circular carbon economy, renewable carbon should not only be used for combustion. It should also be used to replace fossil carbon in chemicals, materials, and liquid fuels.

This is where methanol becomes important. Methanol is one of the most versatile platform molecules in the chemical industry. It is used to produce formaldehyde, acetic acid, plastics, solvents, fuels, and synthetic hydrocarbons. It can also be used as a liquid energy carrier or as a precursor to other fuels and chemicals. Unlike methane, methanol is liquid under ambient conditions, which makes it easier to store and transport. This gives it a practical advantage for decentralized systems, where gas-grid access, compression, transport, or local heat demand may limit the value of biogas.

The importance of methanol is also strategic. Most methanol today is still produced from fossil natural gas or coal. Gelten et al. (2026) note that global methanol production reached roughly 90 million tonnes per year in 2021, with approximately 65% based on natural gas and 35% based on coal. This means that methanol production remains deeply connected to fossil carbon, even though methanol itself could become a renewable carbon carrier if produced from biogenic carbon and low-carbon energy (Gelten et al., 2026).

In this context, biogas creates a new opportunity. It contains both methane and CO₂. These two molecules are often treated separately: methane is upgraded and used as fuel, while CO₂ is removed as an impurity. But from a renewable-carbon perspective, the full biogas stream can be seen as a carbon resource. The question becomes how to transform that resource into the most useful molecule.

3.3 Power-to-Methanol: A Bridge Between Energy and Carbon

Methanol occupies an interesting position in the transition to a circular carbon economy. It is a chemical building block and a liquid carrier of energy and carbon. In that sense, renewable methanol can be seen as a bridge: between fluctuating renewable electricity and storable molecules, between biogenic carbon streams and industrial chemistry, and between today’s fossil-based chemical system and a future in which carbon is used more deliberately.

This perspective formed the basis of the Power-to-Methanol study by Gelten, Hemmer, Aalderink, van Leeuwen, and Kurt (2026), which examined decentralized methanol production in the Netherlands using biogenic carbon from biogas systems. The study compared CO₂ hydrogenation, in which CO₂ separated during biogas upgrading reacts with green hydrogen, with dry methane reforming, in which methane and CO₂ are converted into syngas before methanol synthesis.

Although technically different, the two routes share a common idea. Both connect anaerobic digestion with renewable electricity and chemical production. Biogas is therefore no longer viewed as a fuel or as a source of upgraded biomethane, but as a flexible feedstock for renewable chemicals. This shift is important. It expands the role of anaerobic digestion from waste treatment and energy recovery toward carbon management and molecular value creation.

The study combined techno-economic with life-cycle assessment, using one tonne of methanol as the functional unit. Different electricity sources were considered, including wind, solar, hydropower, nuclear, and fossil-based electricity. This choice was central to the analysis, since Power-to-Methanol uses CO₂ or biogenic carbon. Its environmental performance depends strongly on the origin of the electricity used, especially when hydrogen production through electrolysis is involved (Figure 3).

One of the clearest messages of the study was economic. Under the assumptions used, both methanol routes resulted in a levelized cost of methanol of approximately €2630 per tonne. This was around five times higher than fossil-based methanol. The result does not imply that renewable methanol has no future. Rather, it shows that its competitiveness depends on more than reactor performance or process design alone.

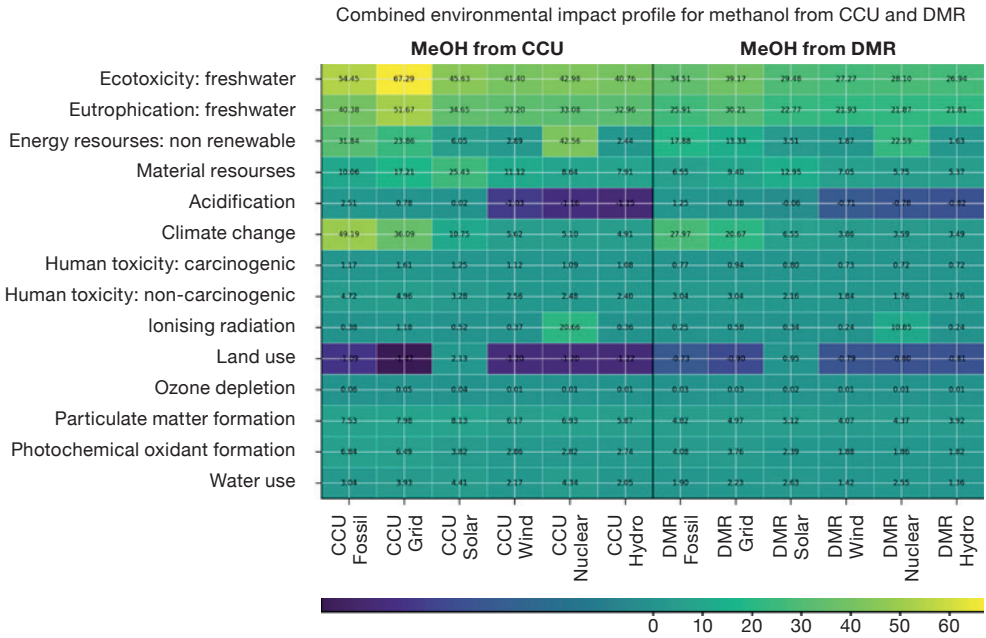


Figure 3 Environmental Footprint impact categories used to compare Power-to-Methanol pathways. The colour scale represents the magnitude of the calculated impact: purple and blue indicate lower values, green intermediate values, and yellow higher values. The colours are comparative, not a simple judgement that a pathway is “good” or “bad”. A multi-category assessment is needed because climate change alone does not capture eutrophication, ecotoxicity, water use and resource impacts. (Adapted from Gelten et al., 2026.)

The dominant cost contribution came from operational expenses, particularly the electricity needed to produce hydrogen. This leads to a simple but important conclusion: the future of renewable methanol will be decided as much by the energy system as by the methanol-production technology. Even an efficient reactor will struggle to produce competitive methanol if renewable electricity is expensive or available for a limited number of hours. Power-to-Methanol therefore becomes most promising where affordable low-carbon electricity, hydrogen production, and methanol synthesis can be closely integrated.

The environmental results added another layer of nuance. Overall, the dry methane reforming pathway performed more favourably than the CO₂ hydrogenation pathway. Yet the life cycle assessment also showed that environmental performance cannot be reduced to climate impact alone. Freshwater ecotoxicity and eutrophication emerged as important hotspots, largely related to digestate application as fertiliser. Just like the biomethanation story, already explained above, the upstream anaerobic digestion system remains decisive, even when the downstream conversion route is technically improved (Figure 3).

This finding connects directly to the broader theme of biogas upgrading and biological methanation. In both cases, downstream conversion increases the potential value of biogas. However, the environmental and economic outcome is determined by the full system: feedstock origin, digestion performance, digestate management, nutrient emissions, hydrogen production, electricity supply, and process integration. The technology pathway cannot be separated from the infrastructure and resource flows in which it is embedded.

Power-to-Methanol therefore teaches an important lesson for the circular carbon economy. Carbon utilisation technologies should not be judged by the molecule they produce, nor only by the carbon they capture. They should be evaluated as part of a wider system in which energy, carbon, nutrients, and local infrastructure interact. In that system, renewable methanol may become a valuable bridge, but if the bridge is built on low-carbon electricity, responsible biomass use, and careful management of the entire biogas chain.

3.4 The Promise and Limitations of Renewable Methanol

Renewable methanol has several qualities that make it attractive in a circular-carbon economy. As a liquid, it is easier to store and transport than biomethane. It is also compatible with established industrial value chains and can serve as a fuel, fuel precursor, or chemical feedstock in sectors where direct electrification is difficult. When produced from biogenic carbon, it can replace fossil carbon in products for which carbon will remain indispensable.

The earlier comparisons, however, show that these advantages do not automatically make decentralized renewable-methanol production technically, economically, or environmentally viable. Its feasibility depends on how the entire production chain is configured. Hydrogen-dependent routes require affordable low-carbon electricity and high equipment utilisation, while their multiple conversion and purification steps increase capital costs, operational complexity, and efficiency losses. These challenges may be manageable within large industrial clusters, where shared hydrogen, CO₂, and energy infrastructure is available, but they can become substantial barriers for smaller and geographically dispersed biogas producers.

Environmental performance must likewise be assessed across the complete value chain rather than inferred from the renewable origin of the product. Benefits from replacing fossil methanol can be weakened by carbon-intensive electricity, inefficient hydrogen production, methane leakage, or poorly managed digestate. The most appropriate production route will therefore depend on local conditions, including the composition and availability of biogas, access to low-carbon electricity, existing infrastructure, plant scale, and the intended use of the methanol.

Variable operation presents an additional challenge. Conventional chemical plants are generally designed to operate continuously, whereas renewable electricity supply and electricity prices fluctuate. Operating methanol plants only during periods of abundant renewable power could reduce electricity costs and associated emissions. They would also lower annual operating hours and leave expensive equipment unused for part of the year. Alternatively, continuous operation would require a reliable electricity supply or sufficient intermediate storage of hydrogen, CO₂, biogas, or syngas. Flexibility is therefore not automatically an advantage: it creates a design trade-off between tracking renewable-electricity availability and maintaining high utilisation of capital-intensive equipment.

The promise of renewable methanol is therefore real but conditional. Current hydrogen-dependent routes are most credible where low-carbon electricity is affordable and consistently available, infrastructure can be shared, and the complete biogas and digestate chain is responsibly managed. For decentralized production, the central research challenge is to simplify the conversion chain and reduce its dependence on externally produced hydrogen without sacrificing carbon efficiency or environmental performance. This provides the rationale for investigating more direct biogas-to-methanol pathways.

3.5 Towards a Direct Biogas-to-Methanol Conversion

The limitations of hydrogen-dependent Power-to-Methanol raise another question: could the methane and CO₂ already present in biogas be converted together into methanol without first separating the gas and producing large quantities of external hydrogen?

This question forms the basis of the proposed direct biogas-to-methanol concept. Biogas consists primarily of methane and CO₂. In conventional valorisation, these components are generally separated: methane is retained as biomethane, while CO₂ is removed and may subsequently be combined with externally produced hydrogen. The proposed technology takes a different approach by treating the complete biogas stream as the feedstock and investigating whether both components can participate in an integrated catalytic pathway toward methanol.

The objective is to use the complementary chemical roles of methane and CO₂. Methane contains both carbon and hydrogen, whereas CO₂ provides an additional source of biogenic carbon but lacks the hydrogen required to form methanol. The scientific challenge is to develop a catalyst and reaction environment that can activate both molecules and redistribute their carbon, hydrogen, and oxygen atoms toward methanol and necessary co-products. Depending on the final reaction pathway, a limited amount of additional hydrogen, steam, oxygen, or another reactant may still be required.

The immediate research goal is therefore to determine whether external hydrogen can be eliminated or substantially reduced while maintaining an acceptable methanol yield, carbon efficiency, and energy demand.

The practical question is straightforward: can raw or minimally treated biogas be converted into renewable methanol through a technically and economically viable process with little or no external hydrogen addition? Such a route could address several practical needs. Biogas producers require higher-value outlets when heat demand is limited or access to electricity and gas networks is constrained. Methanol producers need alternatives to fossil carbon. Catalyst developers must determine whether promising materials can convert realistic mixtures of methane and CO₂ rather than purified laboratory gases (NWO-SIA Projectenbank, 2026).

If successful, this approach could simplify the production chain. It could reduce or avoid separate CO₂ removal, large-scale water electrolysis, hydrogen storage, and some of the compression steps associated with conventional Power-to-Methanol. It would also convert a gaseous and geographically dispersed resource into a liquid chemical that is easier to store and transport. This could give farms, wastewater-treatment plants, and regional digesters an additional route for valorising the full carbon content of biogas.

However, the co-conversion of methane and CO₂ is challenging because both molecules are highly stable. Methane activation means breaking or weakening one of methane's strong carbon-hydrogen bonds so that the molecule can participate in further reactions. CO₂ activation similarly means making this stable molecule reactive enough for its carbon to be incorporated into methanol. The catalyst must activate both molecules at compatible rates and direct the resulting intermediates toward methanol rather than unwanted products.

Selectivity is particularly important. Activating methane does not automatically produce methanol: depending on the catalyst and reaction conditions, it may instead form carbon monoxide, CO₂, hydrogen, light hydrocarbons, or solid carbon. If an oxygen-containing reactant is used, methanol may also undergo further oxidation after it forms. Because methanol is generally more reactive than methane, the catalyst must release or protect the methanol before it is converted into carbon monoxide or CO₂. Selective methane oxidation may therefore be one element of the pathway, but it should be understood within the broader challenge of converting methane and CO₂ together.

Carbon formation requires similar qualification. Solid carbon can be valuable when it is produced intentionally, recovered continuously, and has suitable properties for use as a material. In a reactor designed primarily for methanol production, however, uncontrolled carbon generally accumulates as coke on the catalyst. This blocks active sites, reduces conversion, and shortens catalyst lifetime. It also diverts biogenic carbon away from methanol. Carbon should therefore be considered a potentially valuable co-product if the reactor is deliberately designed to produce and recover it; otherwise, its formation is an unwanted cause of catalyst deactivation.

Real biogas creates an additional challenge because it is not a standardized mixture of methane and CO₂. It can also contain hydrogen sulphide, water vapour, ammonia, siloxanes, and other trace compounds that may poison the catalyst or alter reaction selectivity. The project therefore examines methanol yield, gas-cleaning requirements, catalyst stability, carbon balance, energy consumption, co-product formation, and performance under changing biogas compositions.

The near-term objective is proof of concept rather than immediate commercialization. Work begins by demonstrating whether methane and CO₂ can be jointly converted into methanol with little or no externally supplied hydrogen. It must then identify the reaction pathway, quantify how much of each biogas component enters the methanol, determine the co-products, and establish whether the catalyst remains stable under realistic conditions.

This concept differs from conventional Power-to-Methanol because it does not begin by separating biogas and treating CO₂ as a stream that must be combined with externally produced hydrogen. Instead, it asks whether the methane and CO₂ already present in biogas can be used together as the starting materials for methanol production. If successful, the process could valorise the full biogas stream while reducing one of the highest costs and energy demands of conventional renewable-methanol production: external green hydrogen.

3.6 A Vision for Future Biogas Technologies

The development from biogas to biomethane, from biomethane to methanol, and from hydrogen-dependent conversion to hydrogen-light or hydrogen-free conversion reflects a broader evolution in renewable-carbon thinking.

Anaerobic digestion initially focused on waste stabilization and renewable-energy production, then expanded toward biogas upgrading and biomethane use in existing infrastructure. Current research explores higher-value molecules, including methane from biological methanation and methanol from Power-to-Methanol. A further step may be the direct conversion of raw biogas into liquid fuels and platform chemicals.

This does not mean that biomethane will become unimportant. On the contrary, biomethane will remain essential for energy resilience, seasonal storage, rural energy systems, and fossil natural gas replacement. But methane should not be seen as the endpoint. In some contexts, electricity and heat will be the most useful products. In others, biomethane will create the highest value. In others still, methanol or another renewable molecule may be the better option.

The future of biogas therefore lies in flexibility. A decentralized biogas plant of the future may not be designed around a single product. It may become a local carbon-conversion hub, capable of producing heat, electricity, biomethane, CO₂, nutrients, methanol, or other molecules depending on local demand, infrastructure, policy incentives, and market conditions. Such systems would connect agriculture, wastewater treatment, renewable electricity, chemical production, and circular nutrient management. This is the true meaning of moving beyond biogas. It is not a rejection of biogas, but an expansion of its role. Biogas is the starting point. The larger goal is to direct renewable carbon toward the product that creates the greatest chance of seamless integration: environmental, economic, and societal value.



4. Adding Value to Carbon

4.1 Carbon Capture and Utilisation

As we journey through the energy transition and continue to discover new pathways toward circularity, we arrive at a larger question: Can we really consider any molecule to be waste?

This inquiry has gradually changed the way I think about CO₂. For decades, CO₂ has been viewed primarily as a problem—the gas we measure in emissions inventories, the inevitable product of combustion, and one of the clearest indicators of our impact on climate. And rightly so. Reducing greenhouse gas emissions remains essential if we are to limit climate change.

But there is another way of looking at the same molecule.

CO₂ is not only a byproduct of combustion or an unwanted emission it is also a carbon carrier.

This distinction becomes increasingly important as we move toward a climate-neutral and circular economy. Modern society still depends on carbon-containing molecules. Aviation and maritime fuels, solvents, coatings, pharmaceuticals, polymers, detergents, construction materials, and countless other products require carbon. Electrification can replace fossil fuels in many applications, but electricity cannot replace the carbon atoms needed to make molecules and materials. Breaking our dependence on fossil source-based carbon requires us to find ways to use all its forms.

This shift in perspective opens the door to Carbon Capture and Utilisation (CCU). Rather than treating captured CO₂ as something that must be disposed of, CCU asks whether it can become a feedstock for new products, fuels, chemicals and materials. The European Commission recognises CCU as an important component of industrial carbon management, particularly where captured CO₂ can substitute for fossil-based carbon (European Commission, 2024).

For me, this represents more than a technological development. It represents a change in mindset. The conventional industrial system follows a largely linear carbon pathway: we extract fossil carbon from the Earth, transform it into fuels and products, use them, and eventually return the carbon to the atmosphere as CO₂. A circular carbon system starts from a different premise. Instead of continuously extracting new fossil carbon, we seek to capture carbon already present in our systems, use it again where it creates value, and keep it circulating for as long as possible.

That does not mean that every molecule of CO₂ should be captured and reused. Nor does CCU mean that emissions no longer matter. The priority must always remain avoiding unnecessary emissions and reducing fossil-carbon use. But where emissions cannot be completely avoided, or where carbon is already present in biological and industrial streams, we can begin to ask whether that carbon can be given another life. This is where CCU becomes particularly interesting.

4.2 Why CCU Matters in the Energy Transition

The need for CCU emerges from a simple reality: the energy transition and the carbon transition are related, but they are not the same. Europe is rapidly expanding renewable electricity and developing renewable hydrogen and other forms of renewable energy. The revised Renewable Energy Directive (RED III) sets a binding EU renewable-energy target of at least 42.5% by 2030, with an ambition to reach 45% (European Commission, n.d.-b). At the same time, the European Union has adopted an Industrial Carbon Management Strategy aimed at scaling up carbon capture, transport, utilisation, and storage across Europe (European Commission, 2024). These developments matter because renewable electricity alone cannot solve every part of the transition.

Some industrial processes will remain difficult to decarbonise. Cement, lime, waste treatment, refineries, chemicals, and other industries can generate process emissions that cannot be eliminated by replacing fossil electricity with renewable electricity. The European Commission therefore considers industrial carbon management important for climate neutrality by 2050, particularly in hard-to-abate sectors (European Commission, 2025). At the same time, society will continue to need carbon-containing molecules. CCU sits at this intersection: reducing releases of fossil carbon while supplying carbon for necessary products.

CCU can connect the energy transition with the chemical transition. Renewable electricity and hydrogen can provide the energy and reducing power needed to transform captured CO₂ into molecules such as methane, methanol, and other chemical building blocks. At the same time, the captured carbon can replace some of the fossil carbon that would otherwise be extracted from oil, natural gas or coal.

This is particularly relevant for the renewable-molecule pathways discussed earlier in this book. Biological methanation, renewable methane and methanol demonstrate something more fundamental: *carbon can move through different molecular forms, and each transformation can create a different opportunity for integration*. But this is also where we need to be careful. CCU is not a magic solution.

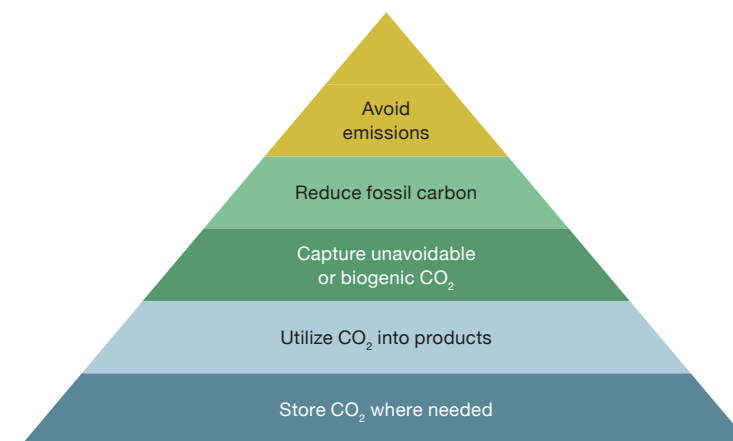


Figure 4 The Carbon-Management Hierarchy (Source: author's conceptualisation)

Capturing CO₂ does not automatically make a product sustainable. The climate benefit depends on where the CO₂ comes from, how much energy is required for its conversion, what source provides that energy, which fossil product is displaced, how long the carbon remains outside the atmosphere, and what happens to the product at the end of its life. Life-cycle assessment is therefore essential in determining whether a particular CCU pathway genuinely delivers an environmental benefit.

CCU should therefore be viewed as part of a broader hierarchy rather than an alternative to emission reduction. Unnecessary emissions should be avoided and fossil-carbon use reduced. Where emissions remain unavoidable, carbon can be captured when appropriate and used where it genuinely replaces fossil resources. When utilisation offers little climate value—or when permanent removal is required—the carbon should be stored (Figure 4). If carbon can be recovered and given another life, what about the other molecules and resources flowing through our energy, water, and waste systems? That question takes us beyond carbon—and into the next stage of the transition.

4.3 The EU Vision: From Carbon Management to Carbon Markets

European policy is increasingly creating the conditions for CCU to become part of industrial strategy. The European Commission's Industrial Carbon Management Strategy, adopted in February 2024, aims to scale up carbon management in the EU and establish a single CO₂ market, including infrastructure for CO₂ transport, utilisation, and storage (European Commission, 2024). The strategy recognises that CO₂ transport infrastructure is a key enabler because captured CO₂ often needs to move from the capture location to a utilisation or storage site by pipeline, ship, rail, or truck (European Commission, 2024, 2025). This is a profound policy development. For many years, CO₂ was mainly discussed as an environmental liability. Now, Europe is beginning to treat CO₂ as an industrial flow. This means that future industry will require CO₂ networks, CO₂ quality standards, CO₂ accounting rules, CO₂ markets, and certification systems for products made from captured carbon.

The Net-Zero Industry Act also strengthens the wider policy landscape by setting a legally binding EU target of 50 million tonnes of annual CO₂ injection capacity by 2030 (European Commission, 2024). Although this target relates to storage capacity, it is also relevant for CCU because capture, transport, infrastructure, certification, and public acceptance are shared foundations of CCS and CCU.

RED III is also important because it supports renewable fuels of non-biological origin, including fuels that can be produced from captured CO₂ and renewable hydrogen (European Commission, 2024, n.d.-b). This creates a direct link between renewable electricity, hydrogen, captured CO₂, and future fuel markets.

The importance of CCU is also increasingly visible in European research and innovation agendas. The Green Deal Projects Support Office describes CCU as a crucial pathway for decarbonising diverse industries, functioning as a bridge between conventional fossil systems and renewable energy systems while supporting both climate objectives and energy security (Green Deal Projects Support Office, 2024). It also highlights that growing applications include CO₂-based synthetic chemicals, fuels, and building aggregates, while stressing that climate benefits depend on the energy source, the product replaced, the carbon intensity of conversion, and the product lifetime (Green Deal Projects Support Office, 2024).

In other words, the EU vision is moving toward an integrated carbon economy. CO₂ will no longer be only measured at the chimney. It will be tracked across value chains.

4.4 From CO₂ Waste to Industrial Feedstock

The idea that CO₂ can be used as feedstock is not new. CO₂ is already used in greenhouses, food and beverages, urea production, and certain specialty processes. However, the scale and purpose of future CCU are different. The future question is whether CO₂ can replace fossil carbon in large-volume products. This is where fuels and platform chemicals become important. Methanol, methane, dimethyl ether, olefins, formaldehyde, oxalate, syngas, and sustainable aviation fuels are not niche molecules. They are part of the foundation of modern chemical and energy systems.

Scientific literature confirms that CCU pathways can convert captured CO₂ into fuels and chemicals but also shows that feasibility depends strongly on energy integration, hydrogen costs, electricity prices, catalyst performance, and life-cycle impacts (Garcia et al., 2024; Yang et al., 2022). Integrated capture and utilisation concepts may reduce some inefficiencies by combining capture and conversion more closely, although further development is needed before broad industrial deployment (Sun et al., 2021).

Future CCU plants are unlikely to operate like the fossil-based refineries of the past. Electricity availability will change. Hydrogen availability will change. CO₂ supply will change. Product demand will change. Energy prices will change. A plant designed for a fossil system could assume relatively stable supplies and predictable operation. A renewable-carbon system will need to respond to a much more dynamic environment. Digital models, flexible process design, storage and buffering, and intelligent system integration will therefore become increasingly important.

In this context, CCU is not a question of chemistry or reactor design. It becomes a question of coordination. The challenge is how to integrate disciplines and technologies. This moves the struggle to understand how molecules, energy, infrastructure, economics, environmental impacts, knowledge, and people can be brought together into a functioning system. Applied science can help create the space between discovery and implementation: taking promising technologies from the laboratory, testing them against real-world constraints, comparing possible pathways, and helping industry and society understand what is technically possible, environmentally meaningful, and economically viable.

The emerging carbon-utilisation activities in the Netherlands offer an example of this broader approach. The HyCARB project represents one of the most important Dutch research initiatives in the field of carbon-based chemistry using captured CO₂, green hydrogen, and renewable electricity. The project brings together companies, SMEs, universities, universities of applied sciences, and research institutes to develop the technology base for industrial end users. The ambition is to develop fuels and platform chemicals from captured CO₂, hydrogen, and green electrons, while combining materials research with techno-economic and life-cycle assessment. Rather than focusing on a single technology, the project brings together questions of carbon availability, renewable energy, process integration, digitalisation, economics, and environmental performance by establishing methods to evaluate scalability. The value lies not in any one component, but in understanding how the components can work together. This way of thinking points toward a broader principle that will return throughout this book: The energy transition will not be delivered by technologies alone. It will be delivered by the systems, institutions, industries and people that learn how to connect them.

4.5 From Laboratory Promise to Practice

If CCU is to become part of the Dutch energy transition, it cannot remain merely a laboratory promise or a policy ambition. It must develop into a practice-oriented innovation field in which technologies, infrastructure, markets, regulations, and industrial needs are considered and developed together. Developing a new technology is the beginning of the journey toward a sustainable energy system. The more important question is what happens next: Can the technology be connected to the systems, infrastructure, resources, people, and markets that surround it?

Current European research increasingly explores pathways in which captured CO₂, renewable hydrogen, and renewable electricity are converted into fuels and platform chemicals through thermocatalytic, electrochemical, and electrically driven processes. Large collaborative programmes now bring together fundamental researchers, technology developers, industrial companies, and applied research organisations to address conversion efficiency, the techno-economic, environmental, and system-level conditions required for industrial deployment. Such initiatives illustrate an important transition in the field: CCU is gradually moving from the question of whether CO₂ can be converted toward the much more demanding one of where, when, and under what conditions CO₂ conversion makes sense.

CCU does not follow a single pathway. Each industrial cluster has different CO₂ sources, different energy conditions, different product opportunities, different infrastructure needs, and different levels of technological maturity. Research on CCU development in the Netherlands shows that the emergence of CCU depends on niche formation, industrial-cluster dynamics, infrastructure availability, stakeholder coordination, and alignment with broader CCS and CO₂ transport systems (Kuipers, 2023). Recent comparative work on CCUS development also shows that Dutch CCU technologies remain less mature than several CCS projects, with deployment affected by high costs, public concern, infrastructure challenges, and uncertain markets (Nurrahmi, 2025). This creates a practical problem.

The Netherlands has strong climate ambitions, industrial clusters, ports, hydrogen plans, and CO₂ storage opportunities. Yet CCU deployment remains fragmented. Some technologies are close to market. Others are still at early technology-readiness levels. Some routes depend heavily on green hydrogen. Others depend more on mineralisation, polymers, direct use, or biological conversion. Some require concentrated industrial CO₂ streams. Others could use biogenic or atmospheric CO₂. Some may create long-lived products. Others produce fuels that release CO₂ again after use.

Fragmentation requires practical methodologies and decision-support tools. Industrial actors need ways to compare utilisation routes, assess technology readiness, evaluate life-cycle impacts, estimate economic feasibility, understand infrastructure compatibility, and identify market opportunities. Policy makers need clearer insight into which CCU pathways contribute meaningfully to emission reduction, industrial competitiveness, and circular carbon value chains. Regional clusters need strategies for connecting CO₂ capture, purification, transport, conversion, storage, and product markets.

4.5.1 Mapping Carbon Flows and Regional Needs

The diversity of technological developments creates a need for an applied research agenda that can determine which technologies should be developed, where they should be located, and how they can be connected to regional infrastructure and markets. Such an agenda begins with understanding regional carbon flows. Fossil, biogenic, and atmospheric CO₂ streams differ in concentration, volume, continuity, and impurity profile. Their locations in relation to renewable electricity, hydrogen infrastructure, ports, chemical industries, and geological storage also shape what can realistically be done with them. Mapping these relationships can help distinguish the carbon streams that are suitable for utilisation from those for which permanent storage may provide greater climate value.

From this regional picture, attention can move toward the available conversion pathways. Their suitability cannot be determined by technological maturity or conversion efficiency alone. Energy and material requirements, life-cycle emissions, economic feasibility, infrastructure compatibility, market demand, and opportunities for regional value creation must be considered together. In some cases, this assessment may identify technologies ready for near-term implementation. In others, it may show that pilot-scale validation or further fundamental research is still required.

These pathways must also be examined under the variable conditions of a renewable-energy system to create the entire value chain. Electricity supply, hydrogen availability, CO₂ composition, energy prices, regulation, and product demand will not remain constant. Scenario analysis, sensitivity assessment, digital twins, and energy and material-flow models can reveal how proposed systems respond to these changes. The aim is not to understand which configurations continue to function and create value when conditions become less predictable.

4.6 When Carbon Should Be Used—or Stored

The answer depends on what the conversion ultimately achieves. When captured CO₂ is used to produce a fuel, the carbon is generally released again when that fuel is burned. This can still benefit the climate if the recycled CO₂ replaces fossil carbon that would otherwise have been extracted, but it does not permanently remove carbon from the atmosphere. Incorporating CO₂ into a long-lived material may store it for much longer, whereas geological storage is intended to keep it isolated for centuries or millennia. Carbon conversion also requires energy and, in many cases, large quantities of hydrogen. Using CO₂ is therefore not automatically the most efficient or environmentally valuable option.

A circular carbon economy consequently requires several complementary strategies. Some captured CO₂ can replace fossil carbon in fuels, chemicals, and materials. Other streams may provide greater climate value when stored permanently. Biogenic carbon—the carbon recently absorbed from the atmosphere by plants—can also be stabilised in soils, materials, or geological formations. The challenge is not to identify one universal solution, but to match each carbon stream with the pathway that creates the greatest climate, environmental, and societal value.

4.6.1 Biochar, BECCS and Hybrid Systems

This question was examined in our recent study of systems combining bioenergy with carbon capture and storage and biochar production (Kir et al., 2026). These approaches both remove biogenic carbon from its short natural cycle, but they do so in different ways.

Biochar is a carbon-rich solid produced by heating biomass under conditions with little or no oxygen, a process known as pyrolysis. Instead of allowing all the carbon in biomass to return rapidly to the atmosphere through decomposition or combustion, pyrolysis retains part of it in a more stable solid form. When biochar is incorporated into soil or suitable materials, some of this carbon can remain stored for decades or centuries. Its permanence nevertheless varies with the feedstock, production conditions, application environment, and biochar properties.

Bioenergy with carbon capture and storage (BECCS) follows another route. Biomass is used to produce energy, and the biogenic CO₂ released during the conversion process is captured rather than emitted. The captured gas is then transported and injected into a suitable geological formation for long-term storage. BECCS therefore combines renewable-energy production with CO₂ removal.

BECCS includes conventional carbon capture and storage (CCS), but the two terms are not identical. CCS describes the process of capturing and geologically storing CO₂, regardless of whether the carbon is fossil or biogenic. If CO₂ from a fossil source is captured and stored, the process primarily prevents additional fossil carbon from entering the atmosphere. In BECCS, the captured carbon originated in biomass that recently absorbed CO₂ from the atmosphere. Permanently storing this biogenic CO₂ can therefore create net carbon removal, if emissions elsewhere in the biomass supply and conversion chain do not outweigh the amount stored.

Biochar and BECCS are often considered separately. The study instead examined a hybrid biochar plus carbon capture and storage system, abbreviated as BC + CCS. In this configuration, part of the biomass carbon is retained in biochar, while CO₂ released from the remaining biomass during energy production is captured and stored underground. The system therefore combines carbon storage in a solid material with geological CO₂ storage within the same biomass-conversion facility.

4.6.2 Why Permanence Matters

The results revealed why the duration of storage matters. The study used a metric called the Climate Effect Value, which compares the climate effect of temporarily or permanently storing carbon with the effect of keeping the same amount of carbon out of the atmosphere permanently. A value close to 1 indicates that the pathway approaches the climate benefit of permanent storage over the period being assessed. Lower values indicate that part of the stored carbon is expected to return to the atmosphere or that the benefit is reduced over time.

Standalone biochar achieved a Climate Effect Value of 0.97 over 30 years, indicating a strong near-term climate benefit. Its value declined over longer periods because part of the biochar carbon was assumed to degrade gradually and return to the atmosphere. BECCS maintained a Climate Effect Value of 0.94 even over 1,000 years because geological storage was assumed to provide much greater permanence. The combined BC + CCS pathway occupied an intermediate position: biochar provided substantial near-term carbon retention, while geological storage preserved part of the removal benefit over much longer timescales (Kir et al., 2026).

These results help explain why not all captured CO₂ should automatically be converted into products. The climate value of a carbon pathway depends on how much carbon is initially captured, and also on how long it remains outside the atmosphere. Carbon incorporated into a fuel may be released within days or months. Carbon in some materials may remain stored for years or millennia. Biochar can retain a substantial share for much longer, while well-managed geological storage is intended to retain CO₂ for centuries or millennia. These pathways may all contribute to climate mitigation, but they do not provide the same service.

4.6.3 Balancing Energy Production and Carbon Storage

The study also demonstrated that the design of the biomass-conversion system changes the balance between energy production and carbon storage. When more biomass was directed toward pyrolysis, a larger quantity of biochar could be produced and applied as a carbon-storing material.

However, allocating more biomass to biochar production also meant that less biomass was available to generate electricity. The system then displaced less electricity from other sources, reducing the avoided-emission benefit associated with renewable power generation.

Pyrolysis temperature created another trade-off. At higher temperatures, a smaller share of the biomass carbon remained in the solid biochar, while a larger share entered gaseous and liquid products. These products could be used as fuels in the integrated facility. Their carbon would normally be released as CO₂ during combustion, but in the modelled BC + CCS configuration, this CO₂ was captured and transferred to geological storage. Higher temperatures could therefore shift carbon from storage in biochar toward storage as captured CO₂. This improved long-term permanence because geological storage is expected to retain carbon longer than biochar.

That outcome does not mean that higher pyrolysis temperatures are always environmentally preferable. Temperature also affects energy consumption, biochar yield and quality, emissions, and the quantity and composition of the gaseous and liquid products. Changing the allocation of biomass between electricity, biochar, and captured CO₂ can improve one environmental indicator while worsening another. The most climate-effective configuration may therefore not be the best-performing option for air quality, resource use, toxicity, or other environmental categories. This is why carbon-removal systems require a complete life-cycle assessment rather than an evaluation based on the amount of CO₂ captured.

These considerations are especially relevant to the Northern Netherlands. The region combines biomass resources, renewable-energy production, ports, industrial clusters, CO₂ infrastructure, and access to potential geological storage. It will therefore face choices among using captured CO₂ for fuels and chemicals, storing it underground, producing biochar, generating bioenergy, producing biomethane, or connecting several of these options in integrated systems. The most appropriate choice will depend on the origin and purity of the carbon stream, the availability of renewable energy, local heat demand, infrastructure, alternative uses of the biomass, environmental impacts, market conditions, and the required duration of carbon storage.

Carbon capture and utilisation and CO₂ removal should therefore not be treated as separate worlds. CCU asks how captured carbon can replace fossil carbon in useful products. CO₂ removal asks how atmospheric or biogenic carbon can be kept out of the atmosphere long enough to counterbalance residual emissions. Biological methanation, renewable methanol, biochar, BECCS, and hybrid BC + CCS systems all form part of the wider challenge of managing carbon deliberately in a climate-neutral society.

The Dutch Carbon Dioxide Removal Roadmap reaches a similar conclusion from a policy perspective. Rapid emission reduction remains the first priority because carbon removal cannot compensate indefinitely for continued avoidable emissions. Nevertheless, some emissions from agriculture, industry, and other difficult-to-decarbonise activities are likely to remain. CO₂ removal must therefore develop as a complementary track within Dutch and European climate policy (Ministry of Climate Policy and Green Growth, 2025).

The future carbon strategy will consequently require a portfolio rather than a single preferred technology. Carbon that can replace fossil feedstocks efficiently may be directed toward chemicals and materials. Carbon used in fuels may contribute to circularity, although its storage is temporary. Other CO₂ streams may create greater climate value through geological storage, while part of the biogenic carbon contained in biomass may be stabilised as biochar. Hybrid systems may combine these functions. The central task is to match each source of carbon with the appropriate product, energy system, storage duration, and regional context.

CO₂ should therefore no longer be treated automatically as waste—but neither should it always be treated as a product. Sometimes utilisation provides the greatest value. In other circumstances, permanent storage is more effective. The strongest solutions may combine carbon utilisation, renewable-energy production, and multiple forms of storage to deliver both immediate climate benefits and long-term carbon removal.

4.7 The Main Challenge: Integration

The main barrier to CCU is often presented as technology. Indeed, many technologies still require significant development. CO₂ is a stable molecule. Hydrogen remains expensive. Electrolysers require large amounts of renewable electricity. Catalysts must operate under realistic conditions. Reactors must handle intermittency. Product purification can be costly. CO₂ sources vary in purity and volume. But the deeper barrier is integration.

A successful CCU implementation must align the source and quality of CO₂; the availability of low-carbon electricity; the way hydrogen is produced, stored, transported and priced; the requirements of the intended product; and the accounting of emissions, avoided emissions, recycled carbon, renewable fuels and carbon stored in products. Without alignment between these systems, CCU may remain technically interesting but commercially and environmentally uncertain. This is why life-cycle assessment and techno-economic assessment are not secondary activities. They are central to responsible CCU development. Studies on CO₂-to-methanol and other utilisation routes show that electricity costs, hydrogen production, heat integration, and environmental burdens strongly influence feasibility and sustainability outcomes (Garcia et al., 2024; Yang et al., 2022). Our BECCS-Biochar study shows the same principle from the carbon-removal side: carbon capture, permanence, substitution benefits, and non-climate impacts must be evaluated together (Kir et al., 2026).

4.8 The Transition to Renewable Carbon

The story of the energy transition is often told as a story of electrons. Wind turbines and solar panels produce renewable electricity. Electrolysers use that electricity to produce hydrogen, while electric vehicles and heat pumps replace technologies based on fossil-fuel combustion. This transition is essential, but it is incomplete. A sustainable economy will also need molecules: renewable fuels for aviation and shipping, chemical feedstocks for materials and manufacturing, and carbon-based products that do not depend on continued fossil-carbon extraction. It will also need ways to connect renewable electricity with industrial demand for carbon. Carbon capture and utilisation offer one pathway toward this future, while CO₂ removal offers another.

The distinction between utilisation and removal matters because humanity has already transferred a vast quantity of carbon from geological reserves into the atmosphere. When captured CO₂ is converted into a fuel, it is generally released again when the fuel is burned. Even carbon incorporated into chemicals and materials may eventually return to the atmosphere when those products are discarded, incinerated, or degraded. Recycling CO₂ can reduce the need to extract additional fossil carbon, but unless that carbon is stored durably, utilisation does not reverse its accumulation in the atmosphere. Limiting further warming requires global net-zero CO₂ emissions, while balancing residual emissions—and potentially reducing atmospheric CO₂ concentrations—requires CO₂ removal (IPCC, 2023).

This need is not explained by climate change alone. Rising atmospheric CO₂ can affect biological systems in less visible ways. A recent study discussed in *de Volkskrant* brought attention to evidence that crops grown under elevated CO₂ concentrations may produce more carbohydrates while containing lower concentrations of protein and important micronutrients. Based on almost 59,000 observations covering 43 crops, ter Haar et al. (2025) found that rising CO₂ directly alters crop nutritional quality, including reductions in nutrients such as protein, iron, and zinc in several important food crops. This means that the consequences of atmospheric carbon accumulation may already be entering society through rising temperatures and extreme weather, and via the composition of the food people eat.



Earth's climatic past provides another warning. The documentary *Die neue Heizeit: Spurensuche in der Vergangenheit*, discussed during Tommy Wieringa's appearance on *Zomergasten*, examined periods in which major disruptions of the carbon cycle transformed the planet. One important example is the Paleocene–Eocene Thermal Maximum, approximately 56 million years ago. A large release of carbon into the atmosphere and oceans was accompanied by substantial global warming, changing rainfall patterns, ocean acidification, declining ocean oxygen concentrations, and major ecological disruption. Reconstructions of this period show similarities between its patterns of temperature and precipitation change and those projected under present-day climate change, although today's conditions and rate of human-driven emissions are not identical to those of the past (Babila et al., 2022; Tierney et al., 2022). The geological record therefore demonstrates that carbon released into the Earth system can alter climate and ecosystems over extremely long periods.

These examples clarify why it would still be insufficient merely to “use all the CO₂.” If every unit of captured carbon could be incorporated permanently into safe and useful products, utilisation could theoretically contribute to durable storage. In practice, however, demand for such products is limited, and many applications retain carbon temporarily. Fuels release it rapidly, short-lived materials delay its release, and certain products can store it for decades or centuries. Meanwhile, continued fossil-carbon extraction adds new carbon to the active atmosphere–ocean system.

Biochar, bioenergy with carbon capture and storage, and hybrid biochar-plus-CCS systems consequently remind us that not all captured carbon should immediately be returned to circulation. Carbon used in fuels may remain outside the atmosphere for days or months. Carbon incorporated into chemicals or materials may remain stored for longer, depending on the product and its end-of-life treatment. Carbon stabilised in biochar or placed in suitable geological formations can potentially remain outside the atmosphere for decades, centuries, or millennia. These pathways serve different purposes: utilisation can reduce demand for newly extracted fossil carbon, whereas durable storage can compensate for residual emissions and begin addressing the excess carbon already added to the atmosphere.

The renewable-carbon transition will require both functions. Carbon should continue to circulate where society genuinely needs it in fuels, chemicals, and materials, but the circulation must increasingly rely on biogenic, atmospheric, or recycled sources rather than newly extracted fossil carbon. At the same time, part of the carbon already moving through the economy must be removed from circulation and stored durably. Therefore, estimating when carbon should be reused, how long it will remain stored in a product, and when permanent removal creates greater climate value becomes a necessity.

The art of the renewable-carbon era will lie in learning when carbon should circulate—and when it should be taken out of circulation.

For the Northern Netherlands, this is more than a technological opportunity. It is a regional opportunity. The region combines renewable-energy potential, hydrogen infrastructure, biomass flows, chemical industry, port logistics, CO₂ sources, and knowledge institutions. Few regions have such a complete foundation for building a renewable-carbon economy.

In this sense, CCU is not the end of the carbon story. If we can transform, utilise, store, or stabilise CO₂ in the right form, in the right place, with the right energy, for the right purpose, and over the right timescale, then CO₂ will no longer be seen only as the symbol of the climate problem. It will become one of the building blocks of the renewable carbon era.

4.9 Why the Northern Netherlands Matters

The Northern Netherlands provides a valuable setting in which the different dimensions of the renewable-carbon transition can be brought together. Its significance does not arise from a single asset, nor does it mean that the region is more important than every other Dutch industrial cluster. Rotterdam–Moerdijk, Chemelot, Zeeland and the North Sea Canal area each possess major industries, infrastructure and carbon-management opportunities. What distinguishes the Northern Netherlands is the regional concentration of energy ports, chemical production, renewable-electricity development, gas expertise, agricultural and biogenic resources, and emerging hydrogen and carbon-management activities.

This combination makes the region a particularly relevant environment for applied research and demonstration. Technologies can be examined as individual processes, as parts of a regional system connecting energy production, industrial demand, ports, agriculture, infrastructure and knowledge institutions. The central opportunity lies in understanding how these elements can reinforce one another.

The region's present position is closely connected to its history. Natural gas shaped the economy, infrastructure and identity of the Northern Netherlands for decades. That history left technical knowledge, companies, pipelines and institutional experience, but also social and environmental consequences that continue to influence the regional transition. There is a need to use this energy-system experience to build new value chains based on renewable electricity, sustainable gases, biogenic carbon and circular chemistry.

The ports of Delfzijl and Eemshaven occupy complementary positions within this transition. Eemshaven combines large-scale electricity generation, connections to offshore energy activities, and an important role in national energy infrastructure. Delfzijl hosts energy-intensive and chemical industries that require both energy and carbon-containing feedstocks. Together with the industrial activities around Emmen, these areas form the Northern Netherlands industrial cluster. The regional Cluster Energy Strategy examines the infrastructure required to decarbonise its industrial and electricity sectors (Planbureau voor de Leefomgeving, 2024).

This industrial and infrastructural combination is relevant to carbon capture and utilisation because CCU requires more than an available source of CO₂. It also needs low-carbon energy to drive conversion processes, suitable infrastructure for transporting electricity, hydrogen, CO₂ and products, and industries capable of using the resulting molecules. The Northern Netherlands contains elements of all these systems within a relatively concentrated geographical area. However, their presence alone does not create a functioning CCU economy. Their value depends on whether they can be connected technically, economically and institutionally.

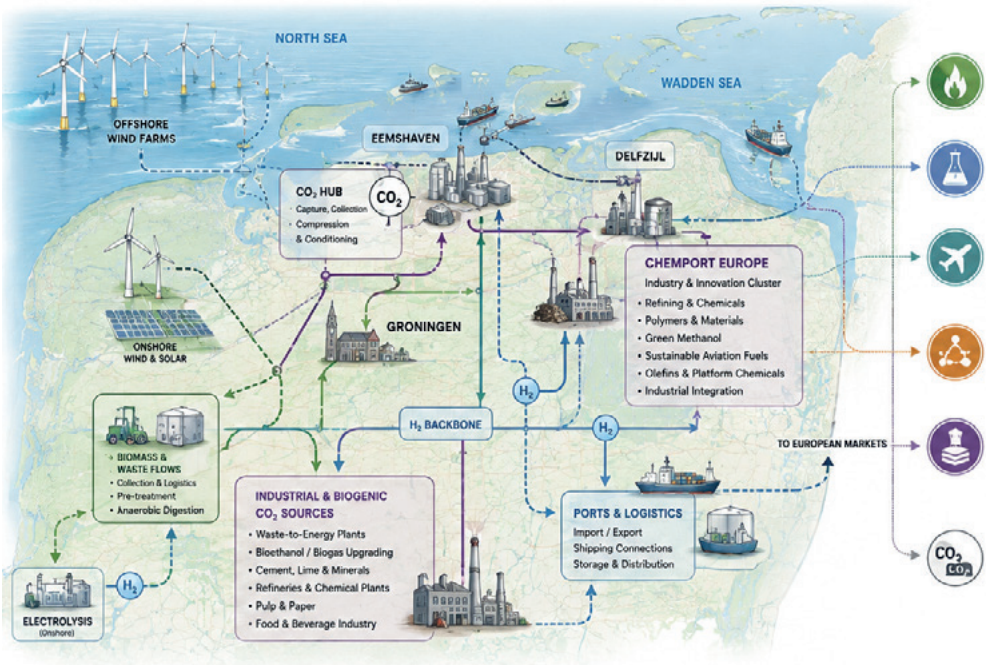
Delfzijl is particularly relevant because it contains an established chemical and industrial ecosystem in which companies exchange energy, raw materials, products and services. Its importance should not be expressed through an uncertain percentage of national chemical production, but through its recognised role within the Dutch industrial-cluster structure. The combination of chemical production, recycling, biobased activities, port access and links to energy infrastructure creates opportunities to test how fossil carbon inputs might gradually be replaced by biogenic, recycled or captured carbon.

The port function strengthens this opportunity. Ports do more than receive and export materials: they connect different transport modes, storage facilities, industrial users and energy networks. Biomass, fuels, chemicals and future hydrogen carriers can move through this infrastructure. Captured CO₂ may be transported toward utilisation or storage, while renewable molecules produced in the region may reach markets that are not connected directly to local pipelines. The ports could therefore become points at which carbon sources, renewable energy and industrial demand are coordinated.

The regional agricultural economy adds another dimension that is less prominent in some of the larger Dutch industrial clusters. Manure, agricultural residues, food-processing streams and sewage sludge can provide biogenic carbon through anaerobic digestion and other conversion processes. Biogas and captured biogenic CO₂ could relate to renewable hydrogen, methanation, methanol production, biochar or carbon-removal pathways. This creates opportunities to link rural resource management with industrial carbon demand. At the same time, the environmental sustainability and availability of these biomass streams must be assessed carefully; their presence should not be interpreted as an unlimited supply.

The Northern Netherlands can consequently be understood as a potential renewable-carbon hub (Figure 5). In such a hub, renewable electricity would remain essential, but it would also be converted into or combined with molecules that serve industrial, transport and storage functions. Captured carbon could be directed toward chemicals, fuels, materials or durable storage according to its origin, quality and potential climate value.

This distinction matters because electricity and molecules provide different services. Electricity can often deliver energy more efficiently where direct electrification is possible. Molecules become especially important where carbon is required as a material building block, where high energy density is needed, or where long-duration storage and long-distance transport justify the additional conversion losses. The purpose of a renewable-carbon hub is therefore not to convert as much electricity as possible into molecules. It is to determine where direct electrification is preferable and where renewable molecules provide functions that electricity alone cannot easily fulfil. If these elements are coordinated successfully, the region can provide an important demonstration of how an established fossil-energy region may evolve into a system that manages renewable energy and carbon together.



Legend: → Biomass/Organic Flows — CO₂ Flows

Potential CCU Products

- | | | |
|--|--|---|
| Renewable Methane
Grid, Heat, Power, Industry | Methanol
Chemicals, Fuels, Shipping | Sustainable Aviation Fuels
Aviation & Long-distance Transport |
| Olefins & Platform Chemicals
Plastics, Polymers, Chemical Industry | Carbon-based Materials
Polymers, Building Materials, Specialty | Permanent Storage
(Where Appropriate)
Geological Storage
Biochar/Mineralisation |

Figure 5 The Northern Netherlands as a potential renewable-carbon hub. The regional combination of the ports of Eemshaven and Delfzijl, renewable-electricity production, chemical industry, hydrogen and gas infrastructure, agricultural biomass, biogenic CO₂ and transport connections creates opportunities for integrated CCU and carbon-removal pathways. (Source: author’s conceptualisation, created through prompting AI tool)



5. Beyond Energy

5.1 Recovering the Resources We Already Have

The energy transition is often described as a transition from fossil fuels to renewable sources of energy. But as we have seen throughout this book, the challenge is becoming broader than replacing one energy source with another. Wastewater, digestate, organic residues, CO₂, nitrogen compounds, phosphorus, heat, biomass, and even water itself are often treated as separate waste-management problems. Yet from a circular-economy perspective, they are interconnected resource streams. The future of sustainability will therefore depend on producing renewable energy, redesigning how society manages materials, molecules, and residual flows.

5.1.1 Wastewater as a Resource

Wastewater is one of the clearest examples of this opportunity. Traditionally, wastewater treatment has been designed around protection: remove pollutants, reduce nutrient concentrations, and return treated water safely to the environment. That function remains essential. But increasingly, wastewater is also being understood as a source of water, energy, carbon, nutrients, and chemical feedstocks. Research into resource recovery has therefore begun to shift the role of wastewater treatment plants from facilities that remove unwanted substances toward systems that can recover valuable resources (Kehrein et al., 2020; Lam et al., 2020).

5.1.2 Digestate, Nitrogen and Phosphorus

The same way of thinking applies to anaerobic digestion. Earlier in this book, we considered digestion primarily as a biological process for converting organic matter into biogas. Yet biogas is one part of what leaves a digester. The remaining digestate contains organic matter, nitrogen, phosphorus, potassium, trace elements, water, and residual carbon. Depending on its composition and treatment, digestate can be returned to agricultural land as a nutrient-rich amendment or further processed to recover more concentrated products. In this sense, the value of anaerobic digestion does not end when the gas leaves the reactor. Digestate is another resource stream waiting to be understood. This broader resource-recovery perspective is particularly important for nitrogen and phosphorus.

Nitrogen is essential for agriculture, but modern agriculture depends heavily on reactive nitrogen fertilisers produced through energy-intensive industrial processes. At the same time, nitrogen is continuously lost from agricultural and wastewater systems, contributing to eutrophication, air pollution, and greenhouse-gas emissions. Recovering nitrogen from wastewater and other residual streams offers an opportunity to reconnect two systems that have become separated: the system that produces food and the system that manages waste. Studies of nitrogen recovery increasingly emphasize that its environmental and economic value depends on the entire system, from the source of the nitrogen and the energy required for recovery to the quality and agricultural performance of the resulting fertiliser (Lam et al., 2020; Spiller et al., 2022).

Phosphorus presents a different but equally important issue. Unlike nitrogen, phosphorus cannot be manufactured from atmospheric resources. It must ultimately come from geological sources, while inefficient use and losses can contribute to water pollution. Europe is also highly dependent on external sources of phosphate rock. Recovering phosphorus from wastewater, sewage sludge, digestate, and other organic residual streams can therefore contribute to circularity and to resource security. A range of approaches, including phosphorus precipitation and recovery of products such as struvite, are being developed to return phosphorus to agriculture in a form that can substitute for part of the demand for mineral fertilisers (Zhu et al., 2023).

This shift is already reflected in European policy. The revised Urban Wastewater Treatment Directive, Directive (EU) 2024/3019, moves beyond wastewater treatment as pollution control and strengthens the role of wastewater systems in circularity, energy neutrality, water reuse, and resource recovery (European Commission, n.d.-c; European Parliament & Council of the European Union, 2024). Similarly, Regulation (EU) 2019/1009 created a framework for marketing EU fertilising products containing recycled and organic materials and promotes recycled nutrients while reducing dependence on imports (European Parliament & Council of the European Union, 2019). But recovery alone is not enough.

5.1.3 Recovery Is Not Automatically Sustainable

A recovered resource is not automatically sustainable. A nutrient recovered from wastewater is not automatically a sustainable fertiliser. A carbon stream captured from an industrial process is not automatically a climate solution. A biomass product is not automatically circular. The environmental value of resource recovery depends on the energy and chemicals required, the presence of contaminants, product quality, transport requirements, substitution effects, market acceptance, and the system boundary used for assessment. Life-cycle assessments generally find significant potential for nutrient recycling, but they also show that outcomes are highly dependent on system design, assumptions, local context, fertiliser substitution, and contaminant accounting (Lam et al., 2020).

This is where the idea of circular agriculture and circular industry becomes important. A circular agricultural system does not seek to produce more with fewer inputs. It seeks to reconnect the flows that have become separated: food production, wastewater, organic residues, energy, carbon, nutrients, water, and soil. Nitrogen and phosphorus can move from farms to households and industries, into wastewater and digestate, and potentially back to agricultural soils. CO₂ can move from biogas upgrading or industrial processes into biological or chemical conversion systems.

Organic matter can move through anaerobic digestion, composting, soil amendment, or biorefineries. Water can be treated, reused, and managed as a resource rather than discharged as a burden. Solving all those needs at once creates value chains. They are the beginning of a transition beyond energy, a transition in which carbon, nitrogen, phosphorus, water, biomass, hydrogen, and organic matter are no longer considered separate waste problems, but interconnected resources. And perhaps this is where the idea of circularity becomes most tangible: not in finding a way to make waste disappear, but in learning how to make resources stay in circulation.

5.2 Renewable Molecules from Residual Streams

The transition from waste treatment to resource recovery requires more than collecting nitrogen, phosphorus, or carbon. It requires the wastewater to become a residual stream for renewable molecules. In earlier chapters, CO₂ was no longer treated as a waste gas. It became a carbon source for methane, methanol, fuels, chemicals, or long-term storage. The same conceptual shift can be applied to nitrogen. Ammonium, nitrate, nitrite, and organic nitrogen in wastewater are not pollutants. They are chemically bound nitrogen resources. This is where new electrochemical, catalytic, and hybrid technologies become important.

5.2.1 From Recovered Nitrogen to Ammonia

The conventional nitrogen economy is built around the Haber-Bosch process, which converts nitrogen and hydrogen into ammonia. This process has transformed agriculture and enabled food production at a global scale. But it also depends heavily on hydrogen, historically produced from fossil natural gas, and therefore carries a substantial carbon footprint. The GroenvermorgenNL project HyNITROGEN directly addresses this problem by targeting low-carbon, flexible nitrogen technologies that use renewable electricity, green hydrogen, nitrogen from air, and nitrogen from wastewater to produce ammonia, nitrogen oxides, and nitrogen-carbon chemicals for fertiliser, sustainable chemical, and energy-storage applications.

The significance of this approach is that it changes the role of wastewater. In a conventional treatment plant, nitrogen is often removed because it can damage receiving waters. In a resource-recovery system, nitrogen is recovered because it can become a valuable molecule. The ambition is to transform recovered nitrogen into useful products.

Ammonia sits at the centre of this story. It is already essential for fertiliser production, and the development of industrial ammonia synthesis through the Haber-Bosch process fundamentally changed global food production by greatly expanding the availability of reactive nitrogen for agriculture (Erisman et al., 2008). At the same time, ammonia is increasingly being explored as a carbon-free energy carrier and hydrogen storage medium because it contains no carbon, has relatively high volumetric energy density, can be liquefied more easily than hydrogen, and can potentially support large-scale and long-duration storage and transport of renewable energy (MacFarlane et al., 2020; Wen et al., 2025). This gives ammonia a dual role. It can support food security through fertiliser production, while also contributing to future energy systems as a carrier for hydrogen and renewable electricity stored in molecular form. Recent reviews emphasize that ammonia can be decomposed to release hydrogen, used directly in fuel cells, or used as a fuel, although each pathway still faces difficulties related to efficiency, safety, emissions control, catalyst development, and infrastructure (Valera-Medina et al., 2018; Wen et al., 2025).

5.2.2 Electrochemical Nitrogen Pathways

Yet ammonia is not the only possible product. Recovered nitrogen can also be converted into nitrate or nitrite products. Electrochemical ammonia oxidation offers one route, in which ammonia is oxidized to nitrite or nitrate in electrolyser systems. Recent reviews describe this route as a potential alternative to conventional nitric acid and nitrate production through the Ostwald process, while also noting that ammonia oxidation can be coupled with hydrogen production at the cathode when used as an alternative anodic reaction in hybrid electrolysis (Cečanaviciute & Schuhmann, 2025). This creates an elegant circular possibility: nitrogen recovered from wastewater could become a fertiliser or chemical product, while the electrochemical system simultaneously supports hydrogen generation within the wider energy system.

Nitrate reduction opens another pathway. Nitrate is often treated as a pollutant because it is highly soluble, persistent in water, and contributes to eutrophication and disruption of the nitrogen cycle. However, electrochemical nitrate reduction can convert nitrate into ammonia, allowing water remediation and nitrogen valorisation to occur in the same process (Niu et al., 2023; Zhong et al., 2024). This changes nitrate from an environmental burden into a chemical feedstock. The challenge is selectivity. Nitrate reduction is an eight-electron process with multiple intermediates and competing reactions, including hydrogen evolution, so catalyst design, reactor configuration, electrolyte conditions, and product separation are all critical for directing electrons toward the desired nitrogen product (Zhong et al., 2024).

5.2.3 Coupling Nitrogen and Carbon

The most fascinating pathway may be the coupling of nitrogen and carbon. If nitrate or nitrite from wastewater can be combined with captured CO_2 , it becomes possible to imagine the production of nitrogen-carbon molecules such as urea. Electrocatalytic C-N coupling from CO_2 and nitrogen-containing species such as nitrate or nitrite has been demonstrated as a possible route to urea synthesis under ambient conditions, offering an alternative to conventional urea production pathways that rely on ammonia and CO_2 in energy-intensive industrial processes (Lv et al., 2021; Paul et al., 2023; Yang et al., 2024). In this case, carbon reduction and nitrate reduction no longer belong to separate worlds. They become part of the same circular chemistry. This is a profound shift. A wastewater treatment plant could become more than a place where pollutants are removed. It could become a place where renewable electricity, recovered nitrogen, captured CO_2 , and hydrogen meet to produce fertilisers and chemicals. The scientific question is removal efficiency and the design of selective, stable, scalable electrochemical systems that can transform residual nitrogen and carbon streams into useful renewable molecules. The HyNITROGEN project will investigate these possibilities further.

This idea connects the biogas story, the CCU story, and the resource recovery story into one system. Biogas provides renewable carbon and energy. CCU provides routes to reuse CO_2 . Wastewater provides nitrogen, phosphorus, organic carbon, and water. Electrochemistry and catalysis provide the tools to transform these flows into renewable molecules. The boundary between waste treatment, energy production, and chemical manufacturing begins to dissolve. But this future will not emerge automatically.

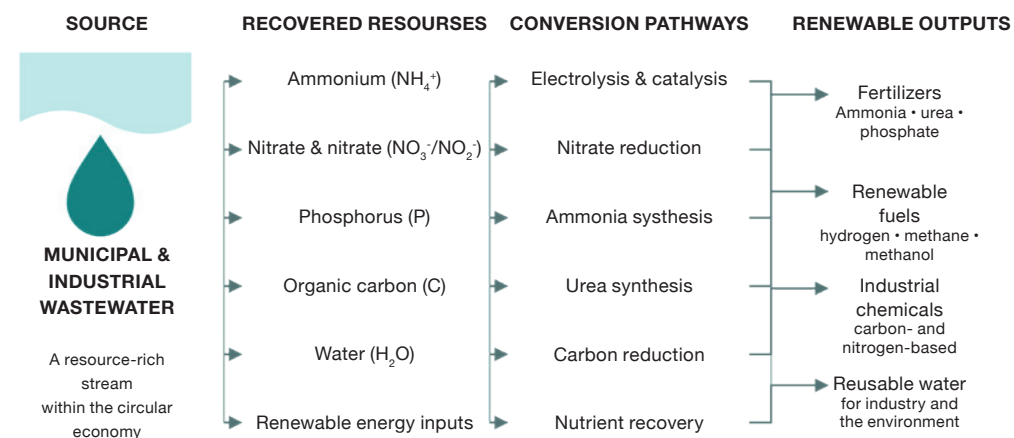


Figure 6 Renewable Molecules from Wastewater (Source: author's conceptualisation)

Recovered resource streams are complex: wastewater contains impurities, electrochemical systems require stable operation, catalysts can be sensitive to feed quality, and recovered products must meet the specifications required for fertilisers or chemicals, while energy demand must remain low enough to ensure environmental and economic viability (Figure 6). Scientific advancement must therefore go hand in hand with assessing how technologies perform in real applications, because technical potential alone does not determine whether a recovered molecule is truly sustainable. Its value depends on product quality, environmental performance, economic feasibility, infrastructure, markets, and policy. The value of a technology is not determined only inside the reactor, but by the value chain created around it.

5.3 Microalgae as a Potential Biological Pathway

Electrochemistry and catalysis offer pathways for recovering resources from wastewater and converting them into renewable molecules. They are not, however, the only possibilities. Biological systems may complement these technologies by using microorganisms to capture carbon and nutrients under different operating conditions. Microalgae provide one example of such a pathway. Their inclusion here does not imply that every renewable-molecule facility must cultivate algae. Rather, they illustrate an option that could be assessed through future research partnerships or integrated regional systems when the available wastewater, CO_2 , land, light and product markets make it appropriate.

Microalgae use light and CO_2 to grow, together with nitrogen, phosphorus and trace elements. Under suitable conditions, they can remove nutrients from water while producing biomass containing proteins, lipids, pigments, carbohydrates and other compounds. Reviews describe their potential contribution to wastewater treatment, CO_2 capture and the production of biofuels, feed ingredients, pigments, bioactive compounds, polysaccharides and other bioproducts (Frongia et al., 2023; Wu et al., 2025). Their distinguishing feature is that resource removal and biomass production can occur within the same biological process: instead of merely separating unwanted substances from water, the system incorporates some of them into a potentially useful product.

This changes how wastewater constituents can be understood. Excess nitrogen and phosphorus may damage aquatic ecosystems, but they are also nutrients required for algal growth. CO₂ contributes to climate change when released into the atmosphere, but it can serve as a carbon source in photosynthetic production. Microalgae may therefore offer a biological connection between wastewater treatment, carbon utilisation, nutrient recovery and biomass production.

A possible integrated system would connect several resource flows. Wastewater or selected liquid side streams could provide water and nutrients, while biogas upgrading or industrial processes could provide a concentrated stream of biogenic CO₂. Renewable electricity might support pumping, mixing, process control and, where justified, supplementary lighting. The resulting biomass could be separated and processed into products appropriate to its quality and composition. Residual biomass unsuitable for higher-value applications might be returned to anaerobic digestion, as long as it creates an environmental benefit and complies with safety requirements.

These connections do not require every process to be located within one laboratory or facility. Microalgae cultivation could take place at a wastewater-treatment plant, greenhouse, industrial site or specialised production facility, while laboratories focusing on renewable molecules could contribute through process evaluation, system modelling, side-stream characterisation or collaboration with external partners.

The concept may be particularly relevant to the Northern Netherlands because the region contains agriculture, wastewater-treatment facilities, biogas production, renewable-energy infrastructure and chemical industries. These activities generate different streams of water, nutrients, CO₂ and organic matter. Microalgae represent one possible way of connecting selected streams, although their suitability would have to be demonstrated for each location.

5.3.1 Conditions for Sustainable Use

Biological origin alone does not guarantee sustainability. Microalgae systems may require considerable energy for mixing, pumping, harvesting, dewatering and downstream processing. Their performance is also affected by land requirements, natural-light availability, seasonal conditions, contamination, biomass quality and access to viable markets. Wastewater-grown biomass may face restrictions in food, feed or other sensitive applications because its composition depends on the contaminants present in the original water. A credible assessment must therefore consider the entire chain, from wastewater and CO₂ supply to biomass separation, processing, product use and management of the remaining residues.

The importance is to understand under which conditions microalgae transform combinations of wastewater, nutrients and CO₂ into products with greater environmental, economic and societal value than the available alternatives. This framing also provides a basis for comparing biological and chemical processes. Relevant criteria include resource-recovery efficiency, energy demand, carbon retention, land and water requirements, contaminant removal, product quality, operating stability, technological maturity and economic viability. Microalgae should therefore be viewed as one candidate within a wider portfolio of resource-recovery technologies.

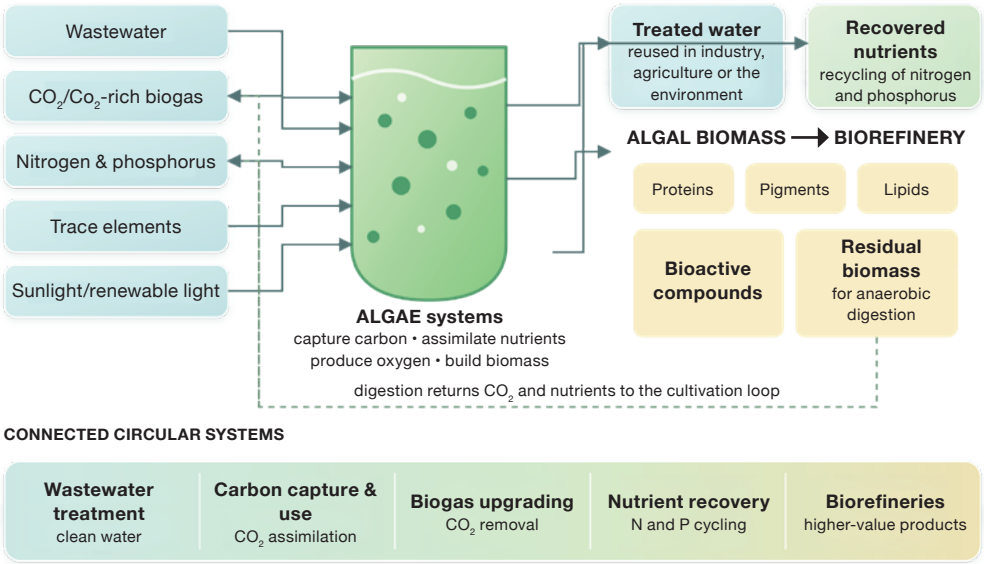


Figure 7 Microalgae as one possible biological resource-recovery platform within a biorefinery.* Under suitable conditions, wastewater nutrients, water, light and captured CO₂ can support biomass production. (Source: author’s conceptualisation)

*A **biorefinery** is a facility or connected group of processes that separates and converts biomass into fuels, chemicals, materials or other useful products.

5.4 Beyond Energy, Towards Resource Circulation

The examples discussed in this book point toward a broader transition from managing individual waste streams to managing connected resource flows. Wastewater, digestate, biogas, captured CO₂ and residual biomass contain different combinations of water, carbon, nutrients and energy. Their value depends on whether something can be recovered safely, efficiently and in a form for which there is a genuine use.

This perspective changes the role of infrastructure. A wastewater-treatment plant must continue to protect public health and receiving waters, and selected facilities may also recover water, nutrients, energy or carbon-containing products. A biogas plant may produce energy while also providing digestate nutrients and a concentrated biogenic CO₂ stream. Farms and food-processing industries may supply organic residues while using recovered water or fertiliser products. Chemical and biological production facilities may transform suitable side streams into new molecules or materials. These functions may be distributed across a region and connected through exchanges of materials, energy, information and expertise.

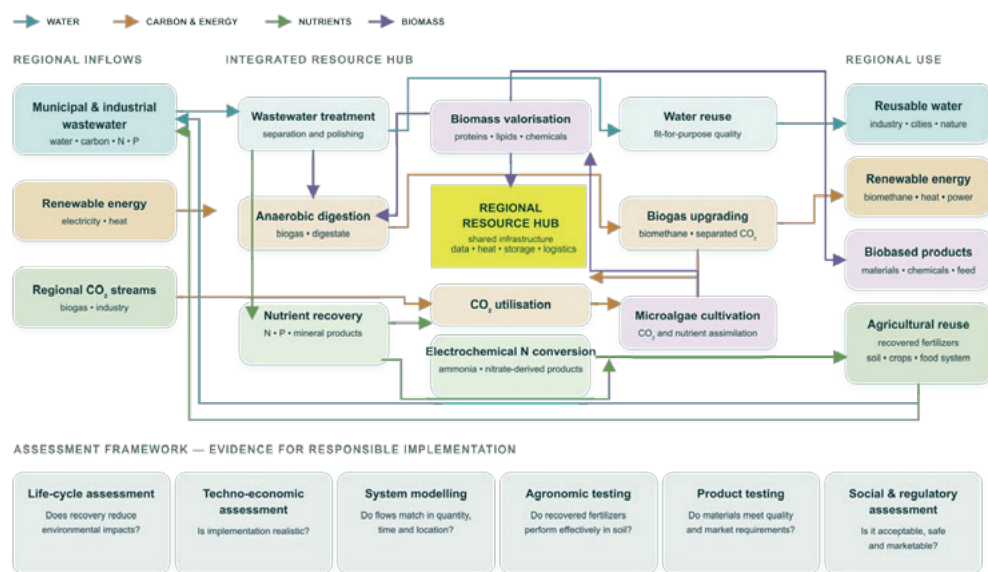


Figure 8 From wastewater treatment to a regional resource hub. Treatment plants, farms, digesters, industrial facilities and biorefineries can exchange water, nutrients, energy, biomass and captured carbon without requiring every process to be located at one site. (Source: author's conceptualisation)

The transition from linear treatment to resource circulation nevertheless requires careful choices. Not every side stream is suitable for recovery, and not every recovered substance has a safe or economically viable market. Biomass availability is limited, renewable electricity has competing uses, clean water is under pressure, phosphorus resources are geographically concentrated, nitrogen losses damage ecosystems, and excess atmospheric CO₂ must be reduced. Recovery should therefore be guided by product quality, environmental benefit, energy use, local demand and the availability of realistic alternatives.

Circularity is consequently a design puzzle rather than an automatic property of a technology. A process may recover one resource while consuming excessive energy or transferring pollution to another stream. An integrated system must therefore be evaluated across its complete life cycle and regional context. The objective is to create connections in which one process genuinely strengthens another—for example, when recovered nutrients replace mineral fertiliser, residual biomass increases biogas production, or biogenic CO₂ becomes a suitable feedstock for another conversion process.



The future resource hub is thus best understood not as one facility containing every available technology, but as a coordinated network. Wastewater-treatment plants, farms, digesters, greenhouses, industrial sites, laboratories and biorefineries may each perform different functions (Figure 8). Their collective value emerges from the way water, energy, carbon and nutrients move between them. Designing these relationships is what allows resource recovery to develop from a collection of promising technologies into a functioning circular system.



6. The Professorship: Scaling Up the Renewable Molecules of the Future

6.1 From Upscaling Bioenergy to Building Renewable-Molecule Systems

When I began this journey, the task appeared relatively simple: *upscale bioenergy*. The phrase suggests a familiar route. A process is developed in the laboratory, made larger, demonstrated, and eventually brought into practice. Yet the story told throughout this book shows why meaningful upscaling is rarely so straightforward. A reactor can be enlarged, but that does not mean that its feedstock will be available, its energy demand will be sustainable, its products will find a market, or its operation will fit the infrastructure around it.

The chapters of this book have gradually widened the scope of that original assignment. Anaerobic digestion showed how organic residues can become biogas while also producing a nutrient-rich digestate. Biological methanation demonstrated that the CO_2 in biogas can be converted into additional renewable methane when renewable hydrogen is available. Methanol opened another possibility: renewable carbon does not have to remain an energy carrier; it can also become a chemical building block. Carbon capture and utilisation extended the discussion to industrial and biogenic CO_2 , while carbon removal reminded us that not all captured carbon should immediately be returned to circulation. The recovery of nitrogen, phosphorus and water then brought energy, carbon and nutrients into the same picture.

Each step led to the same conclusion: Decide which renewable molecules and recovered resources are worth developing, how they can be produced responsibly, and where they create the greatest value.

This leads to the guiding question for the professorship:

How can we identify, develop and integrate—in other words, responsibly upscale— renewable-molecule technologies that respond to the resources, needs and opportunities beginning with the Northern Netherlands—and that can deliver genuine environmental, economic and societal value?

Many technologies can produce renewable energy, convert carbon or recover resources, and more will continue to emerge. The ambition cannot be to develop every possibility. It must be to recognise which pathways deserve attention, improve the technologies that address a meaningful need, and help the strongest options move towards practical application.

The work therefore begins not with a preferred reactor, but with a problem. What molecule or resource is needed? Which feedstocks and side streams are available? What infrastructure already exists? At what scale could the process work? What environmental consequences might follow? Can the product become economically meaningful, and what is preventing implementation? Sometimes one technology will provide the answer. More often, the best solution will emerge from connecting several processes that were previously considered separately.

6.2 A Research Cycle for Responsible Scale-Up

The research programme of the professorship brings together three closely connected activities: assessing technologies, developing them and integrating them at a meaningful scale. These are not separate phases completed once. They form a continuing cycle in which evidence from modelling guides experiments; experimental results improve the models, and demonstration reveals new questions that could not be seen in the laboratory.

Assessment helps us decide where to invest our effort. Process modelling, life-cycle assessment, techno-economic analysis and data-driven methods allow different pathways to be compared before substantial resources are committed. These tools cannot predict the future perfectly, but they can expose hidden energy demands, environmental trade-offs, cost drivers and infrastructure dependencies. They can also show when a promising idea is not yet ready to be scaled—or when it may never be the right solution for a particular setting.

Experimental development becomes necessary when existing technologies cannot meet the requirements revealed by that assessment. Biology, catalysis, electrochemistry, carbon utilisation and resource recovery offer different ways to close those gaps. The aim is not novelty for its own sake. It is to improve conversion, stability, selectivity, flexibility or resource efficiency in response to a real problem.

Integration then tests whether a promising process can function beyond controlled laboratory conditions. Real feedstocks are variable. Impurities enter the system. Electricity prices and renewable-energy availability change. Products must meet specifications. Equipment requires maintenance, operators need clear procedures, and permits shape what is possible (Figure .9). A technology begins to create value when it can work within these realities.

This is the deeper meaning of upscaling. It is not the act of making a reactor larger. It is the process of learning whether a technology can become part of a functioning system.

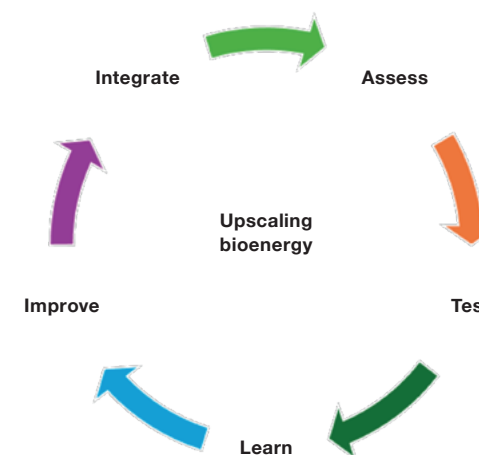


Figure 9 The research cycle for renewable-molecule development. Regional needs and available resources guide technology assessment; assessment identifies development priorities; experiments provide evidence for integration and scale-up; and demonstration generates new data, questions and design improvements. (Source: author's conceptualisation.)

6.3 REMO as an Experimental Bridge

This ambition requires infrastructure. One example of this systems-based philosophy is the **Renewable Molecule Laboratory (REMO)**. A substantial investment by GasTerra enabled Hanze to establish an experimental environment positioned between conventional laboratory research and industrial application. For my professorship, that environment provides an important foundation on which a broader research and innovation programme can be built.

REMO includes infrastructure for work on anaerobic digestion, biological methanation and related renewable-molecule processes, including a trickle-bed reactor and space in which technologies can be connected and tested. Its importance lies not merely in the equipment it contains, but in the questions that the equipment allows us to ask. How does a process behave when its scale increases? Can it tolerate realistic feedstocks and changing operating conditions? What happens when biological and electrochemical processes are connected? Which measurements are needed for reliable control? What would an operator or industrial partner need before trusting the technology?

Projects such as *Watts in Grass*, BIONIC, HyCARB and HyNITROGEN illustrate the wider research directions that can be connected to this environment. Not every activity within these projects must take place physically inside REMO. Some questions belong in smaller laboratories, some in modelling environments and others at external pilot or industrial sites. REMO's role is to provide a place where selected technologies and integrations can advance towards more realistic demonstration.

This distinction is important. REMO should not become a collection of equipment waiting for projects, nor should its future be limited by the equipment installed today. It should develop as an experimental platform through which relevant questions can move between research, education and application. Its value lies in what can be tested there now—and in what can be connected to it in the future.

6.4 The Region as Part of the Research Environment

No laboratory can create a renewable-molecule economy by itself. The next connection must therefore be outward, toward the region in which technologies, infrastructure, industries and communities meet.

The Northern Netherlands offers a distinctive environment for this work. Its history as a natural-gas region has left knowledge, infrastructure and an industrial identity that now need to be redirected towards a different future. The region also brings together renewable-electricity development, agriculture, biomass and biogas resources, industrial and biogenic CO₂ streams, chemical production, emerging hydrogen infrastructure, ports and logistics. These assets do not automatically form a renewable-carbon system. The opportunity lies in learning how to connect them responsibly.

Relationships with Chemport Europe, the industrial cluster around Delfzijl, NOM, Groningen Seaports, the CCU Field Lab and other regional partners allow research to move in both directions. Technologies can travel from the laboratory towards demonstration and industry, but industrial questions must also travel back into research. A variable CO₂ stream may expose the need for a more tolerant catalyst. A biogas producer may require a higher-value product when grid injection is constrained. A company looking for an alternative carbon source may need several conversion pathways to be compared before it invests. An emerging technology may require independent environmental and economic evaluation before a regional partner can judge its relevance.

In this sense, the Northern Netherlands itself becomes part of the research environment. Farms, water authorities, ports, industrial sites, field laboratories, knowledge institutions and companies form a network of places where different parts of the transition can be examined. REMO is one experimental node within that network. My professorship provides a research framework that helps connect the nodes and keeps the larger purpose in view.

6.5 Bridging the Gap Between Discovery and Practice

One of the hardest parts of innovation is bridging the gap between scientific discovery and industrial implementation and tying it to policies. In the laboratory, conditions can be controlled, feedstocks purified, and researchers can intervene as soon as something goes wrong. Industry operates differently. Feedstocks fluctuate, energy prices change, equipment fails, impurities accumulate, regulations apply, and customers expect a consistent product. A process that performs beautifully under ideal conditions may fail when it encounters this complexity. Or even if all work well, maybe a policy is needed for implementation.

Applied research has a particular responsibility in this space. It can preserve scientific rigor while allowing technologies to meet the imperfect conditions of practice. Universities of applied sciences are well placed to support that transition because they can combine experimental research with modelling, environmental and economic evaluation, professional expertise and direct collaboration with industry and government. This work can translate research findings into practical interventions and informed policy advice. Collectively, these efforts can generate meaningful impact by transforming promising innovations into real-world solutions.

6.6 People Are Part of the Infrastructure

Technology is part of the transition. Another form of infrastructure is equally important: people.

The Northern Netherlands will need professionals who can design, operate, assess and improve systems that cross traditional disciplinary boundaries. A biological reactor cannot be separated from process control. A carbon-utilisation technology cannot be judged without understanding energy supply and life-cycle impacts. Nutrient recovery must connect chemistry and biology with agriculture, regulation and product markets. Renewable-molecule systems therefore require people who can work across these boundaries while still understanding the depth of their own discipline.

The professorship brings research and education together to contribute to this human capacity. In learning communities, students, educators, researchers, companies, and policymakers can work on real technological questions. Students can compare possible solutions, conduct experiments, and examine the environmental and economic consequences of their choices. They also learn that real systems rarely behave exactly as textbooks predict. This learning process extends beyond students. Through its research activities and the community, it brings together, the professorship can also serve as a valuable resource for informed decision-making and contribute evidence-based insights to policy discussions and the development of supportive regulatory frameworks.

A field lab like REMO makes this learning tangible, especially when industry stakeholders and end users are involved in the projects. Studying anaerobic digestion or biological methanation in a classroom provides necessary foundations; standing beside a functioning digester or trickle-bed reactor and investigating why its performance changes turns that knowledge into an engineering challenge. Working on such a challenge with researchers, operators, and companies develops more than technical competence. It teaches collaboration, judgment and the ability to learn from incomplete evidence.

The people involved are both the users and part of the research infrastructure. Equipment can be purchased, but a lasting innovation environment must be built through shared knowledge, trust and the capacity to keep learning.

6.7 Beyond the Label of Upscaling Bioenergy

When I look back at the journey described in this book, I no longer see upscaling bioenergy as an adequate label for the full task ahead. It was the starting point, and it remains an essential part of the work, but the research questions have grown beyond it.

The larger mission is to build knowledge and capability around renewable-molecule systems. Sometimes the most valuable product will be methane; in another setting it may be methanol, a recovered nutrient, reusable water, another chemical or durably stored carbon. Sometimes the best outcome will come from connecting several pathways. At other times, the responsible decision may be not to convert a resource at all.

The role of the professorship is to make those choices more informed and their implementation more credible. That means assessing technologies before scaling them, developing them where important gaps remain, testing them under realistic conditions and connecting them to infrastructure, regulation, markets and users. It means bringing industrial problems into research and carrying useful knowledge back into practice. It also means educating people who can continue this work long after an individual project has ended.

Our field lab REMO is an important platform for this mission, but it is not its endpoint. The professorship is not the endpoint of REMO either. Both belong within a larger regional ecosystem of research, education and innovation. Some ideas will begin in our laboratories, move into REMO and continue towards a field lab or industrial demonstration. Others will enter through regional partners and lead us toward new research questions. The movement must remain open in both directions to keep innovation flowing.

This is the future I want my professorship to help build: one in which the Northern Netherlands does produce renewable energy, develops the knowledge, people and infrastructure required to use renewable carbon and other resources wisely. The transition will need renewable molecules, and it will also need the judgment to choose the right molecules, the courage to reject weak pathways, the patience to improve promising ones and the cooperation required to build systems around them.

The energy transition is not achieved when a technology works in a laboratory. It is achieved when that technology becomes part of a system that works for people, industry and the environment. Our task is to invent that future, to test it, learn from it and build it together.

6.8 A Personal Beginning

The journey that brought me here—from the Georgia Institute of Technology to Florida State University in Panama, through the Universidad Tecnológica de Panamá and Middle East Technical University, and eventually to the Netherlands—has been long, unexpected and deeply rewarding. I could not have made it alone.

At every stage, I was fortunate to meet remarkable mentors, collaborators, students, colleagues, friends and supporters who opened doors, challenged my thinking and helped me through difficult moments. Together, we celebrated successful projects, awards and discoveries, but we also learned from experiments that failed and results that forced us to reconsider what we thought we knew. Over time, I came to understand that our best work emerges when we work together and remain willing to learn from one another.

Each answer led to another question, and every discovery made us more aware of how much remains unknown. Far from discouraging me, that realization continues to fascinate and inspire me. I now bring to this professorship everything this journey has given me: knowledge, friendships, lessons, and opportunities. My ambition is to continue the work I have done, but to do it better—to cherish what has already been built, to keep growing and to become an active part of a community committed to meaningful change.

These pages have described what I believe we can achieve together. The next chapter will not be written in words alone. It will be written through the questions we choose the experiments we undertake, the people we educate, the partnerships we build, and the systems we bring into practice.

Now it is time to begin.

Zo gezegd, zo gedaan!

References

- Achinas, S., Martherus, D., Krooneman, J., & Euverink, G. J. W. (2019). Preliminary assessment of a biogas-based power plant from organic waste in the north Netherlands. *Energies*, 12(21), Article 4034. <https://doi.org/10.3390/en12214034>
- Aguirre-Villegas, H. A., Larson, R. A., & Sharara, M. A. (2019). Anaerobic digestion, solid-liquid separation, and drying of dairy manure: Measuring constituents and modeling emission. *Science of the Total Environment*, 696, Article 134059. <https://doi.org/10.1016/j.scitotenv.2019.134059>
- Aieamsam-Aung, P., Srifa, A., Koo-Amornpattana, W., Assabumrungrat, S., Reubroycharoen, P., Suchamalawong, P., Fukuhara, C., & Ratchahat, S. (2023). Upgradation of methane in the biogas by hydrogenation of CO₂ in a prototype reactor with double pass operation over optimized Ni-Ce/Al-MCM-41 catalyst. *Scientific Reports*, 13, Article 9342. <https://doi.org/10.1038/s41598-023-36425-5>
- Alavi, S., Dijk, S., & Kurt, Z. (n.d.). Integrated energy-efficiency and life cycle assessment of decentralized biogas valorization pathways: Trade-offs between CHP, upgrading, and biological methanation [Manuscript submitted for publication].
- Aworanti, O. A., Ajani, A. O., Agbede, O. O., Agarry, S. E., Ogunkunle, O., Laseinde, O. T., Kalam, M. A., & Fattah, I. M. R. (2023). Enhancing and upgrading biogas and biomethane production in anaerobic digestion: A comprehensive review. *Frontiers in Energy Research*, 11, Article 1170133. <https://doi.org/10.3389/fenrg.2023.1170133>
- Babila, T. L., Penman, D. E., Standish, C. D., Doubrawa, M., Bralower, T. J., Robinson, M. M., Self-Trail, J. M., Speijer, R. P., Stassen, P., Foster, G. L., & Zachos, J. C. (2022). Surface ocean warming and acidification driven by rapid carbon release precedes Paleocene-Eocene Thermal Maximum. *Science Advances*, 8(11), Article eabg1025. <https://doi.org/10.1126/sciadv.abg1025>
- Bright Renewables. (n.d.). Biogas upgrading: PurePac. Retrieved August 5, 2026, from <https://www.bright-renewables.com/solutions/renewable-gas/biogas-upgrading/>
- Business.gov.nl. (2024, October 17). Using and spreading manure. <https://business.gov.nl/regulations/using-spreading-manure/>

Business.gov.nl. (n.d.). Manure and fertilisers. Retrieved August 5, 2026, from <https://business.gov.nl/regulations/farming-and-fishing/manure-and-fertilisers/>

Cechanaviciute, I. A., & Schuhmann, W. (2025). Electrocatalytic ammonia oxidation reaction: Selective formation of nitrite and nitrate as value-added products. *ChemSusChem*, 18(10), Article e202402516. <https://doi.org/10.1002/cssc.202402516>

Chemport Europe. (n.d.). Delfzijl. Retrieved August 14, 2026, from <https://www.chemport.eu/locations/delfzijl/>

Dittmer, C., Ohnmacht, B., Krümpel, J., & Lemmer, A. (2022). Model predictive control: Demand-orientated, load-flexible, full-scale biogas production. *Microorganisms*, 10(4), Article 804. <https://doi.org/10.3390/microorganisms10040804>

Dotzauer, M., Pfeiffer, D., Lauer, M., Pohl, M., Mauky, E., Bär, K., Sonnleitner, M., Zörner, W., Hudde, J., Schwarz, B., Faßauer, B., Dahmen, M., Rieke, C., Herbert, J., & Thrän, D. (2019). How to measure flexibility: Performance indicators for demand driven power generation from biogas plants. *Renewable Energy*, 134, 135–146. <https://doi.org/10.1016/j.renene.2018.10.021>

Erismann, J. W., Sutton, M. A., Galloway, J., Klimont, Z., & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1, 636–639. <https://doi.org/10.1038/ngeo325>

European Commission. (2019). The European Green Deal (COM(2019) 640 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640>

European Commission. (2020). A new Circular Economy Action Plan: For a cleaner and more competitive Europe (COM(2020) 98 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098>

European Commission. (2022). REPowerEU Plan (COM(2022) 230 final). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0230>

European Commission. (2024). *Industrial carbon management*. Directorate-General for Energy. https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/industrial-carbon-management_en

European Commission. (2025). About industrial carbon management. Directorate-General for Climate Action. https://climate.ec.europa.eu/areas-action/industrial-carbon-management/about-industrial-carbon-management_en

European Commission. (n.d.-a). *Fit for 55: Delivering on the proposals*. Retrieved August 14, 2026, from https://commission.europa.eu/topics/climate-action/delivering-european-green-deal/fit-55-delivering-proposals_en

European Commission. (n.d.-b). *Renewable energy targets*. Directorate-General for Energy. Retrieved August 14, 2026, from https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en

European Commission. (n.d.-b). *Renewable energy targets*. Retrieved August 5, 2026, from https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-targets_en

European Commission. (n.d.-c). *Urban wastewater*. Retrieved August 18, 2026, from https://environment.ec.europa.eu/topics/water/urban-wastewater_en

European Parliament & Council of the European Union. (2019). Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003. *Official Journal of the European Union*, L 170, 1–114. <https://eur-lex.europa.eu/eli/reg/2019/1009/oj/eng>

European Parliament & Council of the European Union. (2023). Directive (EU) 2023/2413 of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652. *Official Journal of the European Union*. <https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng>

European Parliament & Council of the European Union. (2024). Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment (recast). *Official Journal of the European Union*. <https://eur-lex.europa.eu/eli/dir/2024/3019/oj/eng>

Frongia, F., Cramarossa, M. R., Arru, L., & Forti, L. (2023). Integrated wastewater treatment and CO₂ capture by microalgae-based system. *Journal of Biotech Research*, 14, 227–233.

Garcia, J. A., Villen-Guzman, M., Rodriguez-Maroto, J. M., & Paz-Garcia, J. M. (2024). Comparing CO₂ storage and utilization: Enhancing sustainability through renewable energy integration. *Sustainability*, 16(15), Article 6639. <https://doi.org/10.3390/su16156639>

Gebrezgabher, S. A., Meuwissen, M. P. M., Prins, B. A. M., & Oude Lansink, A. G. J. M. (2010). Economic analysis of anaerobic digestion: A case of Green Power biogas plant in the Netherlands. *NJAS: Wageningen Journal of Life Sciences*, 57(2), 109–115. <https://doi.org/10.1016/j.njas.2009.07.006>

Gelten, H., Hemmer, K., Aalderink, B., van Leeuwen, R., & Kurt, Z. (2026). Limitation of Power-to-Methanol: Identifying the barriers of bridging energy and bio-carbon to produce decentralized renewable methanol via integrated economical and environmental evaluation. *Energies*, 19(7), Article 1626. <https://doi.org/10.3390/en19071626>

Ghiat, I., Banu, A., Bicer, Y., Amhamed, A. I., & Al-Ansari, T. (2025). Circularity within carbon capture networks: A review of capture and utilization technologies. *Journal of CO₂ Utilization*, 95, Article 103075. <https://doi.org/10.1016/j.jcou.2025.103075>

Green Deal Projects Support Office. (2024, February 27). Driving the green revolution: The crucial role of carbon capture and utilisation research & innovation in the EU's industry transition. European Commission Research and Innovation. <https://projects.research-and-innovation.ec.europa.eu/en/strategy/strategy-2020-2024/environment-and-climate/european-green-deal/green-deal-projects-support/green-deal-resources/driving-green-revolution-crucial-role-carbon-capture-and-utilisation-research-innovation-eus>

Groningen Seaports. (n.d.-a). Chemical industry. Retrieved August 14, 2026, from <https://www.groningen-seaports.com/en/for-businesses/industries/chemical-industry/>

Groningen Seaports. (n.d.-b). Hydrogen. Retrieved August 14, 2026, from <https://www.groningen-seaports.com/en/for-businesses/industries/hydrogen/>

Hermann, L., Hermann, R., & Schoumans, O. F. (2019). Report on regulations governing anaerobic digesters and nutrient recovery and reuse in EU member states. Wageningen Environmental Research. <https://doi.org/10.18174/476673>

HoSt Group. (n.d.). Biogas upgrading. Retrieved August 5, 2026, from <https://www.host-bioenergy.com/technology/biogas-upgrading/>

IEA Bioenergy. (2024). Implementation of bioenergy in the Netherlands: 2024 update. https://www.ieabioenergy.com/wp-content/uploads/2024/12/CountryReport2024_Netherlands_final.pdf

Informatiepunt Leefomgeving. (2024). Environment and Planning Act of the Netherlands. <https://iplo.nl/regelgeving/omgevingswet/english-environment-and-planning-act/>

Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report* (Core Writing Team, H. Lee, & J. Romero, Eds.). <https://doi.org/10.59327/IPCC/AR6-9789291691647>

Kehrein, P., van Loosdrecht, M., Osseweijer, P., Garfí, M., Dewulf, J., & Posada, J. A. (2020). A critical review of resource recovery from municipal wastewater treatment plants: Market supply potentials, technologies and bottlenecks. *Environmental Science: Water Research & Technology*, 6(4), 877–910. <https://doi.org/10.1039/C9EW00905A>

Kuipers, C. W. (2023). The development of carbon capture and utilisation in the Netherlands [Master thesis, Delft University of Technology]. TU Delft Repository. <https://repository.tudelft.nl/record/uuid:34c24bce-7914-40e8-833f-0b599f971c6e>

Kir, A. B., Kazanc, F., & Kurt, Z. (2026). Evaluating BECCS-Biochar systems as hybrid negative emission technologies through life cycle assessment. *Energy Conversion and Management*, 368, Article 121992. <https://doi.org/10.1016/j.enconman.2026.121992>

Lam, K. L., Zlatanović, L., & van der Hoek, J. P. (2020). Life cycle assessment of nutrient recycling from wastewater: A critical review. *Water Research*, 173, Article 115519. <https://doi.org/10.1016/j.watres.2020.115519>

Lemes, Y. M., Nyord, T., Feilberg, A., Hafner, S. D., & Pedersen, J. (2023). Effect of anaerobic digestion on odor and ammonia emission from land-applied cattle manure. *Journal of Environmental Management*, 338, Article 117815. <https://doi.org/10.1016/j.jenvman.2023.117815>

Lin, H., Black, M. J., Lin, O., Minter, T., & Borrión, A. (2024). Biogas utilisation: Life cycle assessment of enabling technology for transport biomethane: UK case study, Bore Hill farm Biodigester. *Biomass and Bioenergy*, 190, Article 107402. <https://doi.org/10.1016/j.biombioe.2024.107402>

Lv, C., Zhong, L., Liu, H., Fang, Z., Yan, C., Chen, M., Kong, Y., Lee, C., Liu, D., Li, S., Liu, J., Song, L., Chen, G., Yan, Q., & Yu, G. (2021). Selective electrocatalytic synthesis of urea with nitrate and carbon dioxide. *Nature Sustainability*, 4, 868–876. <https://doi.org/10.1038/s41893-021-00741-3>

MacFarlane, D. R., Cherepanov, P. V., Choi, J., Suryanto, B. H. R., Hodgetts, R. Y., Bakker, J. M., Ferrero Vallana, F. M., & Simonov, A. N. (2020). A roadmap to the ammonia economy. *Joule*, 4(6), 1186–1205. <https://doi.org/10.1016/j.joule.2020.04.004>

Mauky, E., Weinrich, S., Jacobi, H.-F., Nägele, H.-J., Liebetrau, J., & Nelles, M. (2017). Demand-driven biogas production by flexible feeding in full-scale: Process stability and flexibility potentials. *Anaerobe*, 46, 86–95. <https://doi.org/10.1016/j.anaerobe.2017.03.010>

Ministry of Climate Policy and Green Growth. (2025). Netherlands carbon dioxide removal roadmap. Government of the Netherlands. <https://www.government.nl/documents/2025/03/14/netherlands-carbon-dioxide-removal-roadmap>

Ministry of Housing and Spatial Planning. (2026). *Regeling gemeentelijke instrumenten warmtetransitie* [Draft regulation for public consultation]. <https://www.internetconsultatie.nl/rgiw/b1>

Ministerie van Klimaat en Groene Groei. (n.d.). Wet bijmengverplichting groen gas. Wetgevingskalender. <https://wetgevingskalender.overheid.nl/Regeling/WGK025362>

Minister van Klimaat en Groene Groei. (2025, November 9). Energieregeling (BWBR0051774). Overheid.nl. <https://wetten.overheid.nl/BWBR0051774/2026-09-02>

Morey, L., Jiménez-Moya, B., Rodríguez-Abalde, Á., Fernández, B., Artola, A., & Font, X. (2023). Acidification and solar drying of manure-based digestate to produce improved fertilizing products. *Journal of Environmental Management*, 336, Article 117664. <https://doi.org/10.1016/j.jenvman.2023.117664>

Netbeheer Nederland. (2023). *Integrale infrastructuurverkenning 2030–2050: II3050, tweede editie*. <https://www.netbeheernederland.nl/publicatie/ii3050-tweede-editie>

Netbeheer Nederland. (2025). *Netbeheer Nederland scenario's: Editie 2025*. <https://www.netbeheernederland.nl/publicatie/netbeheer-nederland-scenarios-editie-2025>

Netherlands Enterprise Agency. (2026a, February 13). RED sustainability criteria for biomass for the SDE++ scheme. <https://english.rvo.nl/subsidies-financing/sde/apply/red-sustainability-criteria>

Netherlands Enterprise Agency. (2026b). SDE++: Renewable gas. Retrieved August 5, 2026, from <https://english.rvo.nl/subsidies-financing/sde/apply/renewable-gas>

Niu, S., Yang, J., Qian, L., Zhou, D., Du, P., Si, N., Gu, X., Jiang, D., & Feng, Y. (2023). Electrochemical nitrate reduction to ammonia: Recent progress. *ChemElectroChem*, 10(18), Article e202300419. <https://doi.org/10.1002/celec.202300419>

Nurrahmi, R. (2025). A multi-case study of carbon capture, utilization, and storage (CCUS): Case studies from the Netherlands and Indonesia [Master thesis, University of Twente]. University of Twente Student Theses. <https://essay.utwente.nl/essays/108261>

NWO-SIA Projectenbank. (2026). *BIONIC: Biogas to Novel Integrated Catalysis for Biogas* (Dossier GOCH.KIEM.06.002). <https://www.sia-projecten.nl/project/bionic-biogas-to-novel-integrated-catalysis-for-biogas>

Pashchenko, D. (2024). Green hydrogen as a power plant fuel: What is energy efficiency from production to utilization? *Renewable Energy*, 223, Article 120033. <https://doi.org/10.1016/j.renene.2024.120033>

Patel, G. H., Horttanainen, M., Kokko, M., Yörüklü, H. C., & Havukainen, J. (2025). Environmental performance of biomethanation based on life cycle assessment. *Energy*, 320, Article 135244. <https://doi.org/10.1016/j.energy.2025.135244>

Paul, S., Adalder, A., & Ghorai, U. K. (2023). Progress of electrocatalytic urea synthesis: Strategic design, reactor engineering, mechanistic details and techno-commercial study. *Materials Chemistry Frontiers*, 7(18), 3820–3854. <https://doi.org/10.1039/d3qm00433c>

Pierie, F., Benders, R. M. J., Bekkering, J., van Gemert, W. J. T., & Moll, H. C. (2016). Lessons from spatial and environmental assessment of energy potentials for anaerobic digestion production systems applied to the Netherlands. *Applied Energy*, 176, 233–244. <https://doi.org/10.1016/j.apenergy.2016.05.055>

Pierie, F., van Someren, C. E. J., Benders, R. M. J., Bekkering, J., van Gemert, W. J. T., & Moll, H. C. (2015). Environmental and energy system analysis of bio-methane production pathways: A comparison between feedstocks and process optimizations. *Applied Energy*, 160, 456–466. <https://doi.org/10.1016/j.apenergy.2015.09.066>

Planbureau voor de Leefomgeving. (2024). *Reflectie op Cluster Energiestrategieën 2024 (CES 3.0)* (Publication no. 5312). <https://www.pbl.nl/publicaties/reflectie-op-cluster-energiestrategieën-2024-ces-30>

Rawoof, S. A. A., Kumar, P. S., Vo, D.-V. N., & Subramanian, S. (2021). Sequential production of hydrogen and methane by anaerobic digestion of organic wastes: A review. *Environmental Chemistry Letters*, 19, 1043–1063. <https://doi.org/10.1007/s10311-020-01122-6>

Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No. 401/2009 and (EU) 2018/1999 (“European Climate Law”). (2021). Official Journal of the European Union, L 243, 1–17. <https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng>

Saveyn, H., & Eder, P. (2014). End-of-waste criteria for biodegradable waste subjected to biological treatment (compost and digestate): Technical proposals. Publications Office of the European Union.

Spiller, M., Moretti, M., De Paepe, J., & Vlaeminck, S. E. (2022). Environmental and economic sustainability of the nitrogen recovery paradigm: Evidence from a structured literature review. *Resources, Conservation and Recycling*, 184, Article 106406. <https://doi.org/10.1016/j.resconrec.2022.106406>

Sun, S., Sun, H., Williams, P. T., & Wu, C. (2021). Recent advances in integrated CO₂ capture and utilization: A review. *Sustainable Energy & Fuels*, 5(18), 4546–4559. <https://doi.org/10.1039/D1SE00797A>

ter Haar, S. F., van Bodegom, P. M., & Scherer, L. (2025). CO₂ rise directly impairs crop nutritional quality. *Global Change Biology*, 31(11), Article e70568. <https://doi.org/10.1111/gcb.70568>

Tierney, J. E., Zhu, J., Li, M., Ridgwell, A., Hakim, G. J., Poulsen, C. J., Whiteford, R. D. M., Rae, J. W. B., & Kump, L. R. (2022). Spatial patterns of climate change across the Paleocene–Eocene Thermal Maximum. *Proceedings of the National Academy of Sciences*, 119(42), e2205326119. <https://doi.org/10.1073/pnas.2205326119>

Valera-Medina, A., Xiao, H., Owen-Jones, M., David, W. I. F., & Bowen, P. J. (2018). Ammonia for power. *Progress in Energy and Combustion Science*, 69, 63–102. <https://doi.org/10.1016/j.pecs.2018.07.001>

Wen, Z., Huang, B., Wang, Y., Wang, K., Tu, X., Xie, P., & Fu, X. (2025). Ammonia as a renewable energy carrier from synthesis to utilization. *Nature Reviews Clean Technology*, 1, 755–770. <https://doi.org/10.1038/s44359-025-00102-9>

Wu, S., Ye, K., Zheng, X., & Zhao, L. (2025). Microalgal valorization of CO₂: A sustainable pathway to biofuels and high-value chemicals. *Fermentation*, 11(7), Article 371. <https://doi.org/10.3390/fermentation11070371>

Yang, C., Li, Z., Xu, J., Jiang, Y., & Zhu, W. (2024). Electrocatalytic C–N coupling for urea synthesis: A critical review. *Green Chemistry*, 26(9), 4908–4933. <https://doi.org/10.1039/d3gc04920e>

Yang, N., Kang, F., Liu, Z., Ge, X., & Zhou, Y. (2022). An integrated CCU-plant scheme and assessment for conversion of captured CO₂ into methanol. *International Journal of Low-Carbon Technologies*, 17, 550–562. <https://doi.org/10.1093/ijlct/ctac038>

Zhong, W., Gong, Z., Chen, P., Liu, X., Chen, Y., & Lin, Z. (2024). Electrochemical reduction of nitrate to ammonia: From fundamental understanding to practical applications. *Chem Catalysis*, 4(9), Article 101060. <https://doi.org/10.1016/j.checat.2024.101060>

Zhu, F., Kendir Cakmak, E., & Cetecioglu, Z. (2023). Phosphorus recovery for circular economy: Application potential of feasible resources and engineering processes in Europe. *Chemical Engineering Journal*, 454, Article 140153. <https://doi.org/10.1016/j.cej.2022.140153>

Reader's Guide

Glossary of Renewable Molecules

How to Use This Glossary

The definitions below explain how each term is used in the book. They are deliberately brief and written for readers without a technical background. Some terms can have more specialised meanings in scientific, legal, or industrial settings.

A

Acidification: Lowering the pH of a material. In digestate treatment, it can reduce ammonia losses and improve nutrient retention.

Ammonia (NH₃): A nitrogen-containing gas used to make fertilisers and considered as an energy carrier. In high concentrations it can harm health and the environment.

Anaerobic digestion: A biological process in which microorganisms break down organic material without oxygen, producing biogas and digestate.

Article number: A unique number used instead of page numbers to identify some scientific journal articles.

B

Biochar: A carbon-rich solid made by heating biomass with little or no oxygen. It can store carbon and may improve some soils.

Biogas: A gas produced by anaerobic digestion. It consists mainly of methane and carbon dioxide, with small amounts of other compounds.

Biogas upgrading: The removal of carbon dioxide, water, hydrogen sulfide, and other impurities from biogas to produce biomethane.

Biogenic carbon: Carbon that recently came from living organisms, such as plants, manure, or food waste, rather than from fossil fuels.

Biological methanation: The use of microorganisms to combine hydrogen with carbon dioxide and produce methane.

Biomass: Organic material from plants, animals, or biological residues that can be used as a source of energy, carbon, or products.

Biomethane: Methane-rich renewable gas produced by cleaning and upgrading biogas. It can often use the same infrastructure as natural gas.

Biorefinery: A facility or connected system that converts biomass into several useful products, such as fuels, chemicals, materials, and energy.

C

Carbon capture: Separating carbon dioxide from an industrial, energy, or biological gas stream before it reaches the atmosphere.

Carbon capture and storage (CCS): Capturing carbon dioxide, transporting it, and storing it in a suitable geological formation for long-term isolation.

Carbon capture and utilisation (CCU): Capturing carbon dioxide and using it as a feedstock for products such as fuels, chemicals, or materials.

Carbon dioxide (CO₂): A gas released by combustion and many natural and industrial processes. It is also a carbon source for plants and some conversion technologies.

Carbon dioxide hydrogenation: A chemical process that reacts carbon dioxide with hydrogen to produce molecules such as methanol or methane.

Carbon dioxide removal (CDR): Processes that take carbon dioxide from the atmosphere and store it durably in geological formations, soils, biomass, or materials.

Carbon efficiency: The share of carbon entering a process that ends up in the desired product rather than in waste or unwanted by-products.

Carbon monoxide (CO): A reactive, toxic gas containing carbon and oxygen. It is also an important component of synthesis gas.

Carbon neutrality: A condition in which remaining greenhouse-gas emissions are balanced by equivalent durable removals.

Carbon removal permanence: The length of time stored carbon is expected to remain outside the atmosphere.

Carbon sink: A system that absorbs and stores more carbon than it releases, such as a growing forest or geological storage site.

Catalyst: A material that speeds up a chemical reaction or guides it toward a desired product without being consumed in the same way as the reactants.

Catalyst deactivation: The gradual loss of a catalyst's performance, for example through poisoning, fouling, or carbon deposits.

Circular carbon economy: An economy that reduces fossil-carbon extraction by reusing, recycling, and responsibly storing carbon already present in biological and industrial systems.

Circular economy: An approach that keeps products, materials, water, nutrients, and other resources in useful circulation for as long as possible.

Climate Effect Value: A measure used in the book to compare the climate benefit of carbon storage over time with the benefit of permanent storage. Values closer to 1 indicate greater climate benefit.

Co-digestion: Anaerobic digestion of two or more feedstocks together, often to improve gas production or process stability.

Combined heat and power (CHP): The simultaneous production of electricity and useful heat from one fuel, such as biogas.

Compression: Increasing the pressure of a gas so it can be stored, transported, or used in another process.

CO₂-equivalent (CO₂-eq): A common unit that expresses the warming effect of different greenhouse gases as an equivalent amount of carbon dioxide.

D

Digestate: The nutrient-rich material remaining after anaerobic digestion. Depending on its quality and legal status, it may be used or processed as a fertiliser product.

Dispatchable energy: Energy that can be supplied when it is needed, rather than when weather conditions allow production.

Dry methane reforming: A process that reacts methane with carbon dioxide to produce synthesis gas, mainly hydrogen and carbon monoxide.

E

Electrochemical process: A process in which electrical energy drives a chemical reaction, or a chemical reaction produces electricity.

Electrolyser: A device that uses electricity to produce hydrogen from water.

Electrolysis: The use of electricity to split a compound. Water electrolysis separates water into hydrogen and oxygen.

End-of-waste status: A legal classification showing that a recovered material has met defined conditions and can be used as a product rather than regulated as waste.

Energy carrier: A substance or form of energy that can store and transport energy, such as electricity, hydrogen, methane, methanol, or ammonia.

Energy resilience: The ability of an energy system to withstand disruption, maintain essential services, recover, and adapt.

Energy system integration: Coordinating technologies, networks, storage, users, and energy carriers so that they function effectively as one system.

Eutrophication: Excessive nutrient enrichment of water, which can cause algal blooms, oxygen depletion, and damage to aquatic ecosystems.

F

Feedstock: The raw material supplied to a biological, chemical, or industrial process.

Fertiliser product: A material supplied to plants or soils to provide nutrients or improve growing conditions and which meets applicable quality and safety rules.

Flexible feeding: Adjusting when and how much material enters a digester in order to influence biogas production while maintaining biological stability.

Fossil carbon: Carbon from coal, oil, or natural gas that has been stored underground for millions of years.

G

Gas grid: The network of pipelines used to transport and distribute gases such as natural gas or biomethane.

Gas storage: Equipment or infrastructure that holds gas for later use, from small on-site gas holders to large underground facilities.

Green chemistry: The design of chemical products and processes to reduce hazardous substances, waste, energy use, and environmental harm.

Green gas: A general term often used in the Netherlands for renewable gas, particularly biomethane that meets gas-grid quality requirements.

Green hydrogen: Hydrogen produced using renewable electricity, usually through water electrolysis.

Greenhouse gas: A gas that traps heat in the atmosphere, including carbon dioxide, methane, and nitrous oxide.

Grid congestion: A condition in which an electricity or gas network lacks enough capacity to transport all the energy that producers or users want to exchange.

H

Hard-to-abate sector: A sector in which emissions are especially difficult or costly to eliminate, such as aviation, shipping, cement, or some chemical industries.

Hydrogen (H₂): A light gas that can carry energy and supply hydrogen atoms for chemical reactions. Its climate value depends strongly on how it is produced.

Hydrogen sulfide (H₂S): A toxic, corrosive gas with a strong smell that can occur in biogas and must usually be removed before further use.

I

Industrial symbiosis: Cooperation in which the energy, water, materials, or side streams of one company become useful inputs for another.

Intermittency: Variation or interruption in energy production, especially from weather-dependent sources such as wind and solar power.

L

Life-cycle assessment (LCA): A method for evaluating environmental impacts across a product or system's full life, from raw materials and energy inputs to use and end of life.

M

Methanation: The conversion of carbon dioxide or carbon monoxide into methane by reacting it with hydrogen, using either catalysts or microorganisms.

Methane (CH₄): The main energy-containing component of natural gas and biogas. It is also a powerful greenhouse gas when released unburned.

Methane activation: The first chemical step that makes stable methane reactive enough to be converted into another molecule.

Methane leakage: Unintended release of methane from production, storage, transport, or use.

Methanol (CH₃OH): A liquid alcohol used as a fuel, chemical feedstock, and building block for many products.

Microalgae: Microscopic organisms that use light, carbon dioxide, and nutrients to grow. Some systems can combine wastewater treatment with biomass production.

Model predictive control: A control method that uses a model of a process to predict its future behaviour and adjust operation toward a target.

N

Net present value (NPV): A financial measure comparing the present value of future income with present and future costs. A positive NPV generally indicates an economically attractive investment under the assumptions used.

Net-zero emissions: A state in which human-caused greenhouse-gas emissions are reduced as far as possible and remaining emissions are balanced by removals.

Nitrogen recovery: Capturing nitrogen from wastewater, manure, digestate, or other residual streams so it can be reused, for example as fertiliser.

Nutrient recovery: Recovering useful nutrients such as nitrogen and phosphorus from waste or wastewater for reuse.

O

Organic residue: Biological material left after farming, food production, wastewater treatment, or other activities.

Oxidation: A chemical reaction involving the loss of electrons, often associated with reaction with oxygen. Excessive oxidation can turn desired products into carbon monoxide or carbon dioxide.

P

pH: A measure of how acidic or alkaline a liquid is. Low values are acidic, 7 is neutral, and high values are alkaline.

Phosphorus recovery: Capturing phosphorus from wastewater, sludge, digestate, or ash so that it can return to productive use.

Platform chemical: A versatile chemical building block that can be converted into many other products. Methanol is one example.

Power-to-heat (P2H): The use of electricity to produce useful heat, for example with an electric boiler or heat pump.

Power-to-Methanol: A process that uses electricity-derived hydrogen and a carbon source, commonly captured carbon dioxide, to produce methanol.

Power-to-X: A group of processes that convert electricity into another energy carrier, fuel, chemical, material, or form of stored energy.

Pretreatment: A step applied to a feedstock before the main process to improve conversion, remove impurities, or make the material easier to handle.

Process integration: Connecting process steps so that materials, heat, energy, and side streams are used more efficiently across the complete system.

Pyrolysis: Heating biomass or another carbon-containing material with little or no oxygen to produce biochar, gases, and liquids.

R

Ramping speed: How quickly an energy or industrial system can increase or decrease its output.

Reactant: A substance that is consumed or transformed during a chemical reaction.

Reaction selectivity: The ability of a process or catalyst to produce the desired product rather than unwanted alternatives.

RED III: The European Union's revised Renewable Energy Directive, formally Directive (EU) 2023/2413.

Reducing equivalents: Electrons or hydrogen-containing species that supply the chemical reducing power needed to convert a molecule such as carbon dioxide.

Regulatory sandbox: A controlled setting in which new technologies or operating models can be tested under agreed safeguards and monitoring requirements.

Renewable carbon: Carbon obtained from atmospheric, biogenic, or recycled sources rather than newly extracted fossil resources.

Renewable fuel of non-biological origin (RFNBO): An EU regulatory category for renewable fuels made from non-biological energy sources, such as renewable hydrogen and some hydrogen-based synthetic fuels.

Resource recovery: Obtaining useful materials, nutrients, water, energy, or chemicals from streams that would otherwise be treated as waste.

S

SDE++: A Dutch subsidy scheme that supports technologies which reduce greenhouse-gas emissions, including eligible renewable-energy and low-carbon projects.

Seasonal storage: Storing energy for weeks or months so it can be used in another season.

Side stream: A secondary flow of material, water, gas, heat, or energy leaving a process. It may be a waste, by-product, or useful input elsewhere.

Solid carbon: Carbon in a solid form. It can be a useful product when intentionally produced and recovered, but uncontrolled deposits can deactivate catalysts.

Struvite: A phosphorus- and nitrogen-containing mineral that can be recovered from wastewater and used as a slow-release fertiliser where regulations permit.

Synthesis gas (syngas): A mixture mainly containing hydrogen and carbon monoxide that can be converted into fuels and chemicals such as methanol.

T

Techno-economic analysis (TEA): An assessment combining technical performance with costs, revenues, scale, and market assumptions to judge economic feasibility.

Trace compound: A substance present in a very small amount that may still affect product quality, safety, or process performance.

Trickle-bed reactor: A reactor containing packed material over which liquid trickles while gas flows through, creating contact among gas, liquid, microorganisms, or catalysts.

U

Urea: A nitrogen-rich compound widely used as fertiliser and produced industrially from ammonia and carbon dioxide.

W

Waste hierarchy: A preferred order for managing resources: prevent waste where possible, then reuse, recycle, recover value, and dispose as a last resort.

Wastewater treatment: Processes that remove pollutants from used water so it can be safely discharged or reused, increasingly with recovery of energy and materials.

Afterword

My deepest thanks go to my husband, who has stood beside me through demanding projects, international moves, uncertainties, and new beginnings. Thank you for believing in me, even when the road ahead was not yet clear. To our two wonderful and creative boys, Derin and Koray: you bring imagination, energy, and joy into my life. You remind me that the future discussed in these pages is not an abstract idea, but the world that your generation will inherit and continue to shape.

I am profoundly grateful to my mother, father, and sister, whose love and encouragement have remained constant across countries, careers, and distances. I owe a special debt of gratitude to my grandfather, whose unlimited support and confidence in me have provided strength throughout my life and helped make this moment possible.

I also carry with me the memory of my uncle and grandmother—my angels—who would have been immensely proud to witness this inauguration but did not live long enough to see it. Although they cannot be here in person, their love and influence remain an enduring part of me and of the journey that brought me here.

About the Author



Dr. Zohre "Zuzi" Kurt is Professor of Life Sciences and Renewable Energy at Entrance – Centre of Expertise Energy at Hanze University of Applied Sciences in the Northern Netherlands. Her work in Hanze explores how biological resources, residual streams, and captured carbon can contribute to the renewable molecules of the future. Rather than focusing on a single technology, she examines how promising ideas can be developed, evaluated, and connected to the wider systems in which they must ultimately operate.

With degrees in both chemical engineering and environmental engineering, Zohre has always worked at the intersection of disciplines. Her international academic journey has taken her from Middle East Technical University (METU) in Türkiye to the Georgia Institute of Technology in the United States, where she completed a PhD in environmental engineering as well as graduate studies in chemical and biomolecular engineering. She has since conducted research and taught in the United States, Panama, Türkiye, and the Netherlands.

Before joining Hanze, she served as an assistant professor at METU, one of Türkiye's leading research universities. There, she established her own research program, supervised students, and helped secure and develop European research projects, including SolarTwins and C-SINK. In 2022, her academic contributions were recognised with the title of associate professor.

At Hanze, she contributes to major collaborative programmes such as HyCARB, HyNITROGEN, and Watts in Grass. Her research spans renewable methanol, biological methanation, carbon capture and removal, biochar, green hydrogen, sustainable wastewater treatment, nutrient recovery, and the biodegradation of environmental contaminants. A recurring theme throughout her work is the need to connect scientific discovery with industrial practice and regional development.

Her contributions have received international recognition, including a Fulbright Scholarship, the L'Oréal-UNESCO Young Women in Science Award, the Science Academy's Young Scientist Award, the Parlar Research Contribution Award, and advanced-level membership of Panama's National Research System.

Across her research, teaching, and collaborations, one conviction remains central: technology creates meaningful change when it moves beyond the laboratory and becomes part of systems that serve people, industry, and the environment.