ENERGIETRANSITIEFONDS (ETF)

BIJLAGE 4 - Model VOORTGANGS- EN EINDVERSLAG

Voortgangs- / eindverslag m.b.t. voldoening aan de bepalingen en voorwaarden van het subsidiebesluit van Nov 2018, de subsidieovereenkomst en de evaluatie in het licht van de criteria van de projectoproep van Nov 2018 en het KB van 9 mei 2017 die als bijlage van deze overeenkomst werden opgenomen[1]

1. IDENTIFICATIE VAN DE BEGUNSTIGDE(N)

Titel of acroniem van het project: PROCURA

Startdatum van het project: 01/03/2020

Naam en ondernemingsnummer van de begunstigden:
Interuniversitair Micro-Electronica Centrum vzw (IMEC), KBO 0425.260.6683
KU Leuven KBO 0419.052.173
Université de Liège (ULiège), KBO 0325.777.171
WaterstofNet, KBO 0810.768.956
Vlaamse Instelling voor Technologisch Onderzoek (VITO), KBO 0244.195.916
Vrije Universiteit Brussel (VUB), KBO 0449.012.406

Naam van de contactpersoon (SPOC): Joachim John

Datum van dit verslag: 27/03/2025

Indicatie of het gaat om een tussentijds of een eindverslag: eindverslag

2. BEREIKTE STADIUM / FASE IN DE UITVOERING VAN HET PROJECT

Gelieve aan te vinken wat van toepassing is:

x het project werd tot op heden uitgevoerd conform het in het projectvoorstel vervatte actieplan met tijdsschema waarbij de leverbaarheden tijdig werden opgeleverd

ϒ de uitvoering wijkt af van het actieplan zonder dat finaal een belangrijke invloed op het eindresultaat wordt verwacht

ϒ het in het projectvoorstel vervatte actieplan met tijdsschema werd kennelijk niet nageleefd waarbij de voorgedane afwijkingen / afwezigheid van realisaties beduidende implicaties hebben op de uitvoering met een belangrijke invloed op de ingezette middelen

[1] Voor de verantwoording dat voldaan werd aan de budgettaire en financiële criteria dient bijlage 5 bij de subsidieovereenkomst te worden vervolledigd en ingediend.

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Geef een overzicht van de activiteiten uitgevoerd in dit project en leg telkens de link met het oorspronkelijk actieplan/ werkplan en geef aan in welke mate en met welke inspanningen dit gerealiseerd is. Dit overzicht moet toelaten te oordelen of de voorziene middelen werden ingezet voor de activiteiten waarvoor de subsidie was toegekend.

Indien eerder een tussentijds verslag is ingediend, moet de informatie die daarin is opgenomen niet herhaald worden.

3. VOORUITZICHT OP REALISATIE / VALORISATIE VAN HET PROJECT

Gelieve aan te vinken wat van toepassing is:

x de in het projectvoorstel beoogde doeleinden inzake energietransitie en innovatie blijven haalbaar

ϒ er is bijkomende onzekerheid of de beoogde doeleinden inzake energietransitie en innovatie kunnen gerealiseerd worden, maar het project wordt niet ten gronde bijgestuurd

ϒ de beoogde doeleinden inzake energietransitie en innovatie zijn kennelijk niet of onvoldoende haalbaar en het project moet bijgestuurd worden

Geef de belangrijkste resultaten en bespreek duidelijk welke vooruitgang in de verwezenlijking van de projectdoelstellingen reeds is gemaakt. Licht in het bijzonder de belangrijke afwijkingen toe t.o.v. de oorspronkelijke doeleinden inzake energietransitie en innovatie en beschrijf hun impact.

4. GEWIJZIGDE EXTERNE OMSTANDIGHEDEN OF WIJZIGINGEN BIJ DE BEGUNSTIGDEN OF UITVOERDERS

Gelieve aan te vinken wat van toepassing is:

x er zijn geen relevante gewijzigde omstandigheden die de realisatie van het project sterk beïnvloeden

ϒ er zijn wijzigingen bij de begunstigden of uitvoerders maar de realisatie van het project komt niet in het gedrang

ϒ er zijn gewijzigde interne of externe omstandigheden die de realisatie van het project sterk beïnvloeden

Geef bij aankruising van optie 2 of 3 toelichting met betrekking tot het verdere verloop van het project en leg duidelijk de wijzigingen uit ten opzichte van de vooruitzichten bij de start van het project.

5. BEREIKTE RESULTATEN EN BIJDRAGE AAN DE FINALITEIT VAN HET ETF / RESULTS ACHIEVED AND CONTRIBUTION TO THE FINALITY OF THE ETF

Verklaar in welke mate de in het projectvoorstel beoogde doeleinden inzake energietransitie en innovatie zijn bereikt. Licht in het bijzonder de belangrijke afwijkingen toe t.o.v. de in het projectvoorstel beoogde doeleinden toe en beschrijf hun impact. Lijst daartoe alle in het oorspronkelijk werkplan vooropgestelde leverbaarheden op met indicatie welke daarvan werden opgeleverd en heldere toelichting van de resultaten / conclusies die daaruit voort vloeiden.
Explain to what extent the objectives regarding energy transition and innovation envisaged in the project proposal have been achieved. In particular, explain any significant deviations from the objectives envisaged in the project proposal and describe their impact. To this end, list all deliverables proposed in the original work plan, with an indication of which of them were delivered and a clear explanation of the results / conclusions that resulted from them.

De begunstigde licht toe in welke mate de bereikte resultaten van het project een significante en positieve impact hebben op België en dus op de Belgische energiebevoorradingszekerheid en / of het netevenwicht in het licht van de finaliteit van het Energietransitiefonds. In dat opzicht wordt eraan herinnerd dat de finaliteit van het Energietransitiefonds in de parlementaire voorbereiding van de wet van 28 juni 2015 houdende diverse bepalingen inzake energie werd beschreven als volgt: "Dit fonds zal instaan om onderzoek en ontwikkeling aan te moedigen in innoverende projecten in het energiedomein en onder meer om energieproductie en – opslag aan te moedigen" en in het regeerakkoord van 10 oktober 2014: "Om de bevoorradingszekerheid op lange termijn te verzekeren, *kiest de Regering voor een overgang naar een duurzaam energiesysteem. Deze overgang moet technologieneutraal zijn. Er wordt daarbij volop ingezet op onderzoek en ontwikkeling naar een verbreding van de energiemix, […].”*

The beneficiary explains to what extent the results achieved by the project have a significant and positive impact on Belgium and therefore on the Belgian energy supply security and/or the grid balance in the light of the finality of the Energy Transition Fund. In this regard, it is recalled that the finality of the Energy Transition Fund was described as follows in the parliamentary preparation of the law of 28 June 2015 containing various provisions on energy: “This fund will be responsible for encouraging research and development in innovative projects in the energy domain and, among other things, to encourage energy production and storage" and in the coalition agreement of October 10, 2014: "To ensure long-term security of supply,
the Government opts for a transition to a sustainable energy system. This transition must be technology neutral. There is a lot of focus on research and development to broaden the energy mix, […].”

Progress report per work package

Final report

(please provide your input here)
Proposed structure:

- *Introduction/Motivation from original proposal*
- *Work performed as proposed in the task description.*
- *Results and conclusions benchmarked with the deliverables and milestones in the proposal text*
- *Potential impact of your results on the Belgian energy production and -storage for long term security of supply*

WP1 Carbon Capture (Gregoire Leonard, Kim So-Mang, (ULiege))

<u>*Summary of the main results:*</u>

In the final year of the PROCURA project, **WP1** focused on evaluating selected **CO_2 capture (CC) technologies** (MEA, Selexol, PolyActive/ Polaris membranes, DAC) in the **Belgian context** using the **Decision Support Tool (DST)** with Analytical Hierarchy Process (AHP) developed in previous years. While numerous publications exist on CC technologies, a comprehensive database and standardized methods for fair technology comparison are still lacking. Selecting the most appropriate technology depends on multiple factors, such as technology maturity levels (TRLs), CO_2 concentrations in flue gas, flow rates, energy consumption, and environmental impact, making the selection process complex and time intensive. Therefore, the goal is to provide decision-makers with a structured framework to fairly compare various CC options, enabling technology rankings for a given scenario and supporting the identification of the most suitable CO_2 capture applications. To assess CC technologies in the Belgian context, case studies were developed using anonymized industrial data from various sectors with different CO_2 concentrations and capture scales to identify the most suitable capture technologies. Additionally, Monte Carlo simulations were applied to the DST to analyze the sensitivity of technology rankings when AHP weights are varied, ensuring robustness in decision-making. Shortcut correlations of selected CC technologies, developed in this work, are integrated into the DST database to accurately reflect cost and technical performances under various industrial scenarios and operating conditions. The applicability of the DST is demonstrated through case studies, providing recommendations to support the technology selection process.

Project achievements towards the objectives

The following table provides an overview of the WP1 tasks, summarizing key objectives and deliverables.

Table WP1-1: Overview of WP1 tasks and deliverables.

Task	Details and Deliverables
1.1 Technology Screening	A review of existing and/or promising CO_2 capture technologies
1.2 Point source Technologies	The development of process models to supply material and energy balances for the CO_2 technologies (for the Belgian context). Detailed TEAs of selected carbon capture technologies
1.3 Direct Air Capture (DAC)	A single-column DAC unit simulation model was developed to provide mass and energy balances for DAC performances
1.4 Technology Comparison	The comparison of the different technologies in terms of engineering, energy, economics, and environmental criteria within the framework of DST to provide technology rankings at a given flue gas conditions (CO_2 concentrations and flue gas flow rates)
1.5 Belgian Case Study	The development of case studies for the Belgian context, targeting representative CO_2-emitting industries

- Task 1.1: A review of existing and/or promising CO_2 capture technologies involving literature study and screening of CO_2 capture technologies has been conducted throughout the project years, and a summary is presented in the supporting document. Besides the technology review, one of the key factors influencing the capture cost is a selection of the CapEx/ OpEx estimation method. A summary of the related literature on the CapEx/ OpEx estimation methods is presented in the supporting document.

- Task 1.2: Large point-source CO_2 capture has been studied through modeling and detailed TEA studies on the selected carbon capture processes, including chemical absorption (MEA), physical absorption (Selexol), PolyActive membrane, and Polaris membrane technologies. The simulation results (mass and energy balances, economics) were then used to develop shortcut correlations to evaluate the cost of the technology at various CO_2 concentrations (mol%) and capture sizes. These correlations are in the process of being published, where the MEA correlations are in the second round of the reviewing process with a publisher, while a paper for the rest of the selected technologies is under internal review. This work will be used as a method framework that will be applied to other technologies, such as other chemical solvents.

- Task 1.3: This task has been completed in the previous years (2 and 3), where a small-scale DAC process model has been developed and validated with experimental data obtained from the literature. Based on this model, a large-scale DAC model was developed and published as conference proceedings. The results of Task 1.3 are implemented in the DST database, and the results will be a good comparison against point-source capture technologies. Results related to the DAC are provided in the supporting document.

- Task 1.4: In the final year, the DST has been further developed by coupling the developed shortcut correlations of the selected CC technologies in the DST database to dynamically update the database based on the user inputs (e.g. flue gas conditions and user preference scores for weight calculations). Therefore, besides technology comparison between the chemical and physical solvents, the selected

CC options can be dynamically compared within the same basis in the DST where these CC technologies are compared in terms of engineering, energy, economics, and environmental criteria, and the DST can provide technology rankings at given user inputs. Besides the shortcut correlation-based technologies used in the DST, literature-based CC technology databases (cryogenic and calcium looping) are coupled with the DST to demonstrate the capacity of the DST to handle different types of data. The results of this task will be written as a third journal article to demonstrate the DST via case studies considered in Task 1.5 below. More details of the latest DST are provided in the supporting document.

- Task 1.5: To evaluate carbon capture technologies in the Belgian context, four case studies were conducted using anonymized industrial data from multiple sectors, considering varying CO_2 concentrations and capture scales to determine the most suitable capture technologies. Also, industrial emission profiles used in WP3 were used with the shortcut correlations of the selected CC technologies to identify feasible capture options across industries in Belgium.

Results and Discussions

A. Shortcut correlation of the selected CC technologies

Based on the correlation formats used in the previous years (Eq. 1 and 2), the same approach applied to the MEA process was used to develop correlations for other CC technologies including post/ pre- combustion Selexol processes and polymeric based CC membranes (PolyActive and Polaris processes). The TEC represents the total equipment cost of a considered capture technology and α, β, γ, *n* and *m* are the fitting parameters. The latest fitting parameters are presented in Table WP1-2 below.

$$\text{TEC} = \alpha + (\beta \cdot x_{co_2}{}^{n} + \gamma) \cdot F^{m} \qquad \text{Eq. (1)}$$

$$\text{specific energy requirement} = \alpha \cdot e^{n x_{co_2}} + \beta \cdot e^{m x_{co_2}} \qquad \text{Eq. (2)}$$

Table WP1-2: Correlation fitting parameters for the selected CC technologies

Process	α	β	γ	n	m	x_{co_2} [mol %]	F [Nm³/h] [a]
					TEC [M€$_{2023}$] [b]		
MEA	1.756	0.0083	-0.0053	0.1115	0.8049	$5 \le x_{co_2} \le 50$	$4\,035 \le F \le 1\,613\,808$
Selexol (Post.)	-0.0957	0.0025	0.0070	0.9578	0.5958	$15 \le x_{co_2} \le 70$	$2\,873 \le F \le 538\,205$
Selexol (Pre.)	0.1451	1.7914	-1.7892	0.0003	0.6832	$15 \le x_{co_2} \le 70$	$2\,873 \le F \le 538\,205$
PolyActive[c]	6.1991	0.0023	0.0035	2.5067	0.6783	$5 \le x_{co_2} \le 70$	$2\,865 \le F \le 1\,613\,808$
Polaris[c]	8.6156	0.0009	0.0002	0.8186	0.7450	$5 \le x_{co_2} \le 70$	$2\,865 \le F \le 1\,613\,808$
					Specific Cooling Duty $\left[\frac{GJ}{t_{co2}}\right]$		
MEA	10.040	2.905	—	-33.73	0.2108	$5 \le x_{co_2} \le 50$	$4\,035 \le F \le 1\,613\,808$
Selexol (Post.)	3.782	1.0360	—	-6.524	-0.1464	$15 \le x_{co_2} \le 70$	$2\,873 \le F \le 538\,205$
Selexol (Pre.)	0.4412	2.4860	—	0.7562	-3.4020	$15 \le x_{co_2} \le 70$	$2\,873 \le F \le 538\,205$
PolyActive	17.64	2.8400	—	-18.14	-1.6180	$5 \le x_{co_2} \le 70$	$2\,865 \le F \le 1\,613\,808$
Polaris	14.11	2.0470	—	-19.15	-1.4190	$5 \le x_{co_2} \le 70$	$2\,865 \le F \le 1\,613\,808$
					Specific Reboiler Duty $\left[\frac{GJ}{t_{co2}}\right]$		
MEA	1.471	3.560	—	-35.83	-0.0158	$5 \le x_{co_2} \le 50$	$4\,035 \le F \le 1\,613\,808$
					Specific Electrical Duty $\left[\frac{kWh}{t_{co2}}\right]$		
MEA	10.420	2.164	—	-23.49	-1.2350	$5 \le x_{co_2} \le 50$	$4\,035 \le F \le 1\,613\,808$
Selexol (Post.)	5411	71.79	—	-20.95	-1.0880	$15 \le x_{co_2} \le 70$	$2\,873 \le F \le 538\,205$
Selexol (Pre.)	468.7	63.73	—	-12.92	-0.9637	$15 \le x_{co_2} \le 70$	$2\,873 \le F \le 538\,205$
PolyActive	2401	396.10	—	-17.88	-1.3890	$5 \le x_{co_2} \le 70$	$2\,865 \le F \le 1\,613\,808$
Polaris	1058	160.60	—	-20.38	-0.5061	$5 \le x_{co_2} \le 70$	$2\,865 \le F \le 1\,613\,808$

[a] Although the full ranges for CO_2 concentration and flow rates are given in the present table, it is important to recall that for each concentration, the correlation is only valid within the annual capture scale of 31 - 1250 kt/y, as indicated by the ranges presented in Table 9
[b] For the TEC, $\alpha + (\beta \cdot x_{co_2}{}^{n} + \gamma) \cdot F^{m}$ format is used while for the specific duties, $\alpha \cdot e^{n x_{co_2}} + \beta \cdot e^{m x_{co_2}}$ format
[c] For the membrane systems, the TEC correlations presente rest of the equipment cost without the total membrane costs.

Currently, no standardized methods for estimating capital expenditures (CapEx) and operational expenditures (OpEx) exist in the literature. To ensure consistency and minimize discrepancies arising from varying methodologies and assumptions, it is crucial to apply a uniform CapEx and OpEx estimation approach throughout a study. By using the shortcut correlation developed in WP1, a consistent framework is provided, allowing users to apply their chosen CapEx/OpEx estimation method systematically.

As a demonstration, these correlations have been applied using the DOE/NETL CapEx estimation method to assess the carbon capture cost (€/tCO_2) of various technologies across different CO_2 inlet concentrations in flue gases, representing emissions from different industrial sources. The analysis is conducted under user-defined economic assumptions, such as a low-pressure steam price of 7 €/GJ and an industrial electricity price of 0.102 €/kWh in Belgium. The overall capture costs (with compression costs) for the evaluated carbon capture technologies at different CO_2 concentrations are presented in Figure WP1-1.

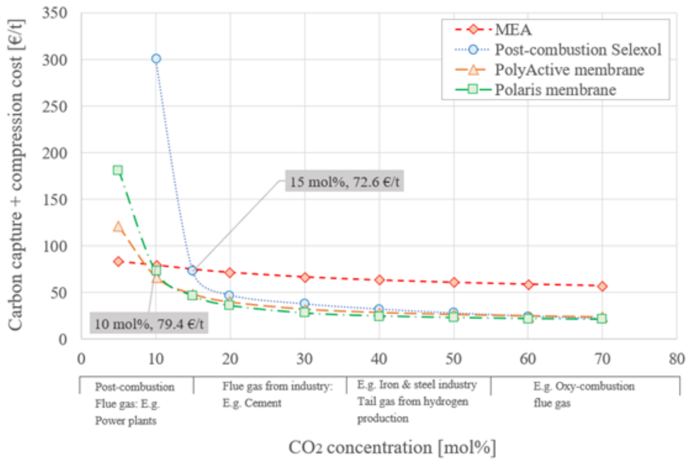


Figure WP1-1: Carbon capture and compression cost of the selected CC technologies across CO_2 inlet concentrations [mol%]

At CO_2 concentrations ≤15 mol% (typical in power plant flue gases), MEA remains the most viable option due to its high TRL and low capture costs (Figure 1). PolyActive and Polaris membranes show potential, with capture costs dropping sharply around 10 mol% and declining gradually thereafter. However, with a TRL of 6 and no large-scale deployments, their costs may be underestimated due to limited real-world data. For CO_2 concentrations >20 mol% (e.g., cement or steel flue gases), Selexol and membranes become more cost-effective than MEA, with capture costs falling to ~30 €/tCO_2 beyond 30 mol%. While qualitative guidelines exist for selecting capture technologies by CO_2 concentration, quantitative boundaries remain undefined. Expanding this study to more technologies under comparable conditions would enhance cost-effective selection based on CO_2 concentration and capture scale.

B. Decision Support Tool (DST) and Belgian case studies

This case study investigates the techno-economic performance of four industrial plants in Wallonia, Belgium, considering different CO_2 concentrations and capture scales. The goal is to assess carbon capture cost at selected industrial plants and to identify favoured capture technologies considering not only capture cost (economics) but also other factors, including engineering, energy, and environmental criteria. Common economic assumptions are presented below.

Table WP1-3: Correlation fitting parameters for the selected CC technologies

Parameters	Assumptions
CEPCI: 2023	789.2
Lifetime of the project [y]	30
discount rate [%]	8.5
Operating hours [h/y]	8766
Cooling water [€/GJ]	0.40
Low Pressure Steam [€/GJ]	7.00
Electricity [€/kWh]	0.102

The selected plants represent a diverse set of industrial scenarios with varying flue gas compositions and CO_2 capture scales:

- **Plant A:** Low CO_2 concentration (5%) with a capture scale of 0.1 Mt/y.

- **Plant B:** Moderate CO_2 concentration (10%) with a capture scale of 0.2 Mt/y.
- **Plant C:** High CO_2 concentration (20%) with a capture scale of 0.1 Mt/y.
- **Plant D:** Higher CO_2 concentration (30%) with a capture scale of 0.03 Mt/y (30 kt/y).

For each plant, selected CC correlations (Corr.) will be used to estimate capture costs, while the DST will identify feasible options by considering both capture costs and other KPIs from engineering, energy, and environmental criteria. More details of the selected KPIs can be found in the supporting document. Technical and economic results for MEA, Selexol, and membrane technologies are estimated using the correlation parameters in Table 2 above, where the DOE/NETL method is applied to derive final CapEx from TEC estimates. For DAC, simulation-based (Sim.) results from Task 1.3 are used, while literature-based (Lit.) data (Element Energy, 2014) were implemented for cryogenic and calcium looping processes. OpEx in Table 4 includes fixed O&M (estimated using Turton et al., 2008) and variable operating costs (utility costs). Additional KPI values not listed in Table 4 are available in the supporting document. The Selexol correlation applies to concentrations ≥15 mol%, so it is pre-screened out for the Plant A case (5% inlet concentration).

Table WP1-4: KPIs of selected CC technologies for Plant A case

Technology	Data Type	TRL	Spe. Heating duty	Spe. Electrical duty	Spe. CapEx	Spe. OpEx	Capture cost
Units		[1-9]	[GJ/t]	[kWh/t]	[$€_{2023}$/t]	[$€_{2023}$/t]	[$€_{2023}$/t]
MEA	Corr.	9	3.80	5.25	544.2	78.60	129.6
Selexol (Post-comb.)*	Corr.	9	NA	NA	NA	NA	NA
Membrane (PolyActive)	Corr.	6	0	730.5	499.3	135.2	182.0
Membrane (Polaris)	Corr.	6	0	538.5	849.9	184.2	263.8
DAC (Sorbent)	Sim.	7	12.14	691.7	550.8	174.5	538.1
Cryogenic	Lit.	6	0	560.5	634.4	105.4	164.8
Calcium Looping	Lit.	6	4.20	83.3	310.6	77.8	106.9

*Due to the low inlet concentration of 5%, the Selexol technology is pre-screened.

Membrane technology is generally more feasible for gas streams with high CO_2 concentrations (above 20%). The estimated capture costs for the PolyActive and Polaris membrane options are 182.0 $€_{2023}$/t and 263.8 $€_{2023}$/t, respectively, both higher than the MEA capture cost of 129.6 $€_{2023}$/t (Table 4). For cryogenic and calcium looping technologies, results were derived from literature-based CapEx and energy consumption data (see supporting document), with CapEx harmonized using the DOE/NETL method for consistency. Literature suggests that both cryogenic and calcium looping technologies could be viable alternatives to MEA. However, as these technologies remain at the pilot scale (TRL 6), large-scale industrial deployment is unlikely in the near term. Notably, calcium looping benefits from low specific CapEx and OpEx, achieving the lowest estimated capture cost of 85.5$€_{2023}$/t, making it a key driver for ongoing research in looping technologies. Still, the reliability of these estimates must be validated with real-world plant data. For DAC, a key advantage is its ability to capture CO_2 from any location without site-specific land constraints. However, current capture costs remain high, though projections suggest they could decrease to around 100 €/t in the next phase of development (Climeworks, 2023). This reduction could make DAC a viable option in the near future.

To demonstrate the DST in the technology selection process, arbitrary weights are calculated by providing user preference comparison values to the DST, where AHP is applied to provide both criteria and KPI weights as follows:

Weights of Criteria

Engineering	34.1%	Energy	20.3%	Economics	28.6%	Environment	17.0%

Weights of KPIs

TRL	62.8%	Thermal req.	37.6%	CO_2 Capture cost	54.0%	Carbon footprint	33.3%
Purity	8.6%	Electrical duty	47.4%	Spe. CapEx	16.3%	Safety Issue	33.3%
SOx NOx [ppm]	28.5%	Cooling duty	14.9%	Spe. OpEx	29.7%	Installation area	33.3%

Figure WP1-2: An example of AHP weights obtained from the DST based on user preferences

The user preference comparison values are selected in such a way that they resulted in more weights in engineering criteria (34.5%) with a high emphasis on the TRL (62.8% of KPI weight under the engineering criterion), electrical duty (57.1% of KPI weight under the energy criterion), and capture cost (64.8% of KPI weight under the economic criterion). For the environmental KPIs, equal weights of 33.3% were given. Based on this set of weights, the DST was used to identify suitable capture technologies at a flue gas CO_2 concentration of 5% and a capture scale of 0.1 Mt/y. The technology overall score (global overview) and the criteria performances are presented in Figure WP1-3.

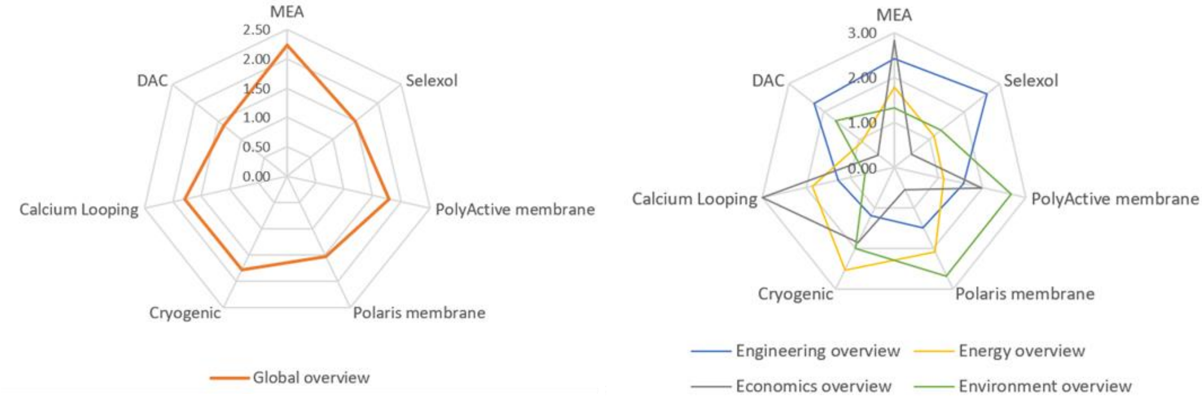


Figure WP1-3: Spider web diagram for technology scores and rankings for Plant A

The spider web diagram compares carbon capture (CC) technologies based on multiple KPIs. MEA achieves the highest overall score (2.17), followed by the PolyActive membrane and calcium looping, while cryogenic, Polaris membrane, and Selexol rank lower. MEA excels in economic and engineering aspects, but scores lower in energy and environmental criteria. Calcium looping performs well in economic and energy metrics but has a low TRL. DAC ranks 7th, with strong engineering performance but high energy use and costs. Membrane technologies (PolyActive and Polaris) offer strong environmental scores but face economic challenges due to high CapEx and OpEx, particularly at low CO_2 concentrations. PolyActive and Polaris membranes also differ in operational parameters: PolyActive operates at 4 bar with higher electricity consumption (730.5 kWh/t), whereas Polaris operates at 1 bar with lower energy use (538.5 kWh/t). Cryogenic processes show balanced but lower scores due to their TRL of 6. Overall, MEA remains the most viable, while PolyActive and calcium looping show economic potential if calcium looping's literature-based assumptions hold at 5 mol% CO_2.

A sensitivity study using a Monte Carlo simulation (10,000 runs) tested the robustness of rankings by varying AHP weights while maintaining a Consistency Ratio (CR) ≤ 0.1. The DST, implemented in MATLAB, evaluated ranking stability under different weight distributions. Box plots illustrate variations in Monte Carlo-generated weights. More details on AHP methodology are in the supporting document.

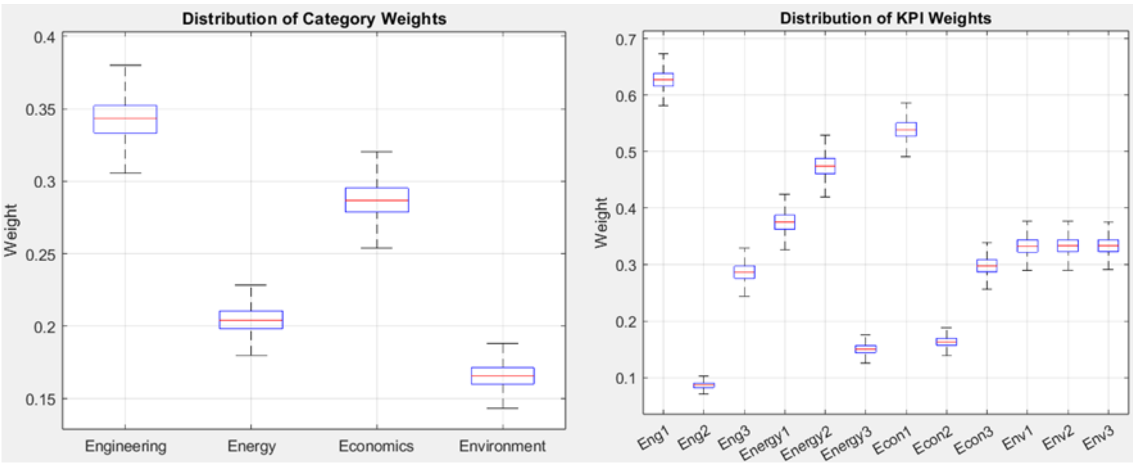


Figure WP1-4: Distribution of AHP weight variations using Monte Carlo simulation

The stacked bar chart (Figure WP1-5) showed the impact of Monte Carlo simulations on the ranking stability of various CO_2 capture technologies under uncertainty in AHP weight assignments. The results indicate that MEA and PolyActive membrane processes maintained stable rankings (1st and 2nd, respectively), while calcium looping and cryogenic technologies competed with each other with rankings of 3 and 4 across all simulation runs, although cryogenic was ranked 3rd in about 80% of the runs, reflecting its sensitivity to weight variations. As expected from the DST results, DAC consistently ranked the lowest due to its high capture cost, with a similar trend observed for Selexol at a low concentration of 5 mol%. These findings highlight that the top two technologies maintained stable rankings despite perturbations in AHP weights, whereas some technologies were more sensitive to variations. This underscores the importance of carefully assigning weights in the decision-making process.

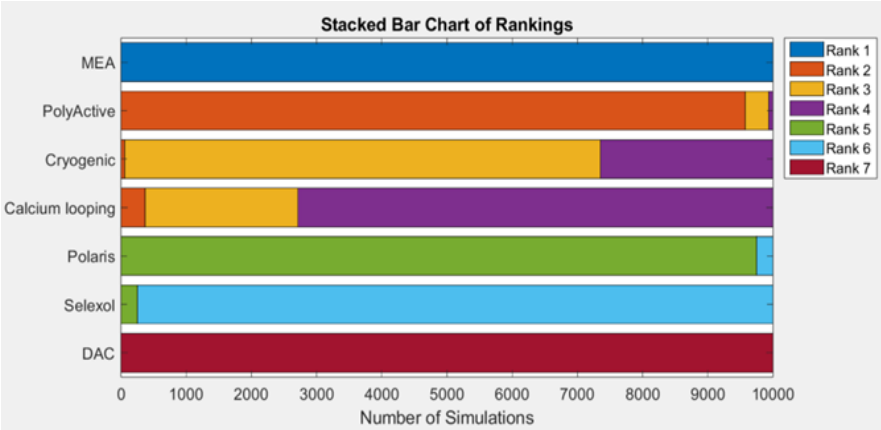


Figure WP1-5: Monte Carlo simulation results on the AHP weights and technology rankings

For Plant B – D, the same methodology was applied to identify suitable CC options at the given flue gas characteristics. The results can be found in the supporting document.

C. Carbon Capture profile across Belgian industries

Based on the Belgian emission profiles across different industries, shortcut correlations developed in WP1 were used to identify economically feasible CC options across the Belgian industries. An example of the capture cost profiles is presented in Figure WP1-6, and the rest of the results can be found in the supporting document.

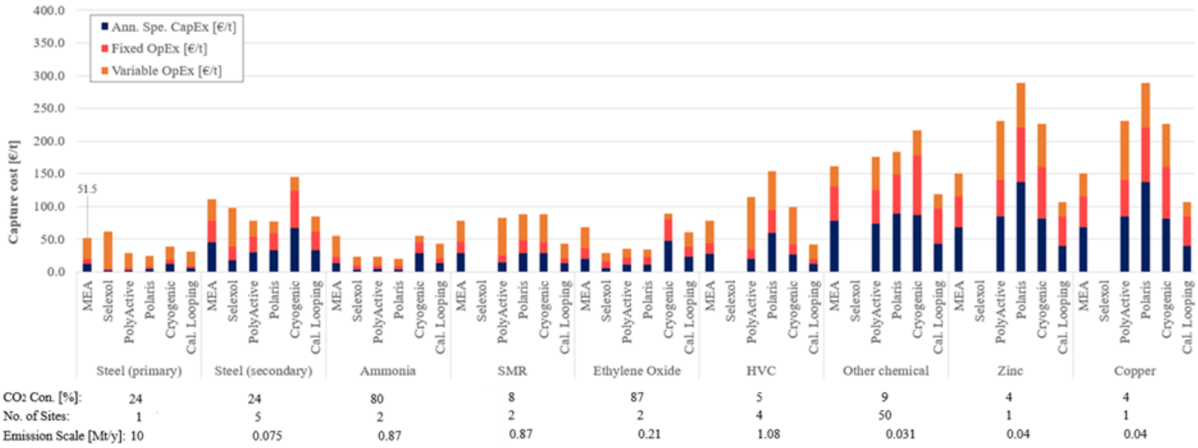


Figure WP1-6: Carbon capture cost profiles across the Belgian industries

The capture cost varies significantly across different industries, influenced by CO_2 concentration and emission scale. Generally, industries with higher CO_2 concentrations and larger emission scales, such as steel and ammonia, exhibit lower capture costs, whereas industries with lower CO_2 concentrations and smaller emission scales, such as zinc and copper, tend to have higher costs. The cost distribution among technologies also varies across sectors, visually highlighting feasible capture options. In particular, the Selexol process is pre-screened for sectors with low inlet CO_2 concentrations. The breakdown of costs into CapEx and OpEx components points out the capital-intensive nature of some technologies (e.g., Polaris membrane), particularly in sectors with lower CO_2 concentrations. This information can be presented as a heatmap table to easily identify economically feasible options across the industries, and an example is presented in the supporting document.

Conclusions and Perspectives

Carbon capture (CC) technologies play a crucial role in mitigating climate change by reducing CO_2 emissions from large industrial sources. As the global urgency to address environmental challenges increases, there is a growing need for effective tools and frameworks to evaluate and select the most appropriate CO_2 capture solutions for various industrial sectors. The complexity of this task lies in the diverse technological options available, each with varying levels of maturity, energy requirements, costs, and environmental impacts. While significant research has been conducted on CC technologies, a gap remains in providing a comprehensive, standardized approach to fairly comparing and selecting the most suitable technologies for specific industrial applications. Decision-makers are often faced with the challenge of navigating these complexities, making the process of choosing the right technology both time-consuming and uncertain.

This work aims to address this gap by presenting the Decision Support Tool (DST) and shortcut correlations developed over the course of the PROCURA project. By creating a structured framework that incorporates key performance indicators (KPIs) such as technology maturity, capture cost, energy consumption, and environmental impact, this work package aims to provide decision-makers with a robust tool to make informed, data-driven choices. The case studies and sensitivity analyses conducted as part of this work will offer valuable insights into the practical application of CC technologies in the Belgian context, helping to guide the selection of optimal solutions for reducing industrial CO_2 emissions.

To further enhance the applicability of the DST, future work should expand the scope of technology options by incorporating alternative capture methods such as potassium carbonate absorption and hybrid technologies (e.g., membrane-solvent or membrane-cryogenic systems). This would allow for a more comprehensive and fair comparison of a broader range of CC technologies. Additionally, the assessment could be extended beyond capture costs by integrating pre-treatment, transportation, and storage costs. This holistic approach would provide decision-makers with a global overview of the economic and logistical challenges associated with CC implementation, ultimately improving the strategic deployment of CO_2 capture solutions. Furthermore, other multi-criteria decision analysis (MCDA) methods, such as TOPSIS, could be applied to evaluate various capture options and compare the rankings to the AHP-based results. Lastly, the environmental impact of CC options can be evaluated using Life Cycle Assessments (LCAs) to understand detailed trade-offs in resource consumption, emissions, and overall sustainability, while the social impact of capture technologies can also be included in the DST to provide a robust comparison framework considering the multi-dimensions of CC deployment.

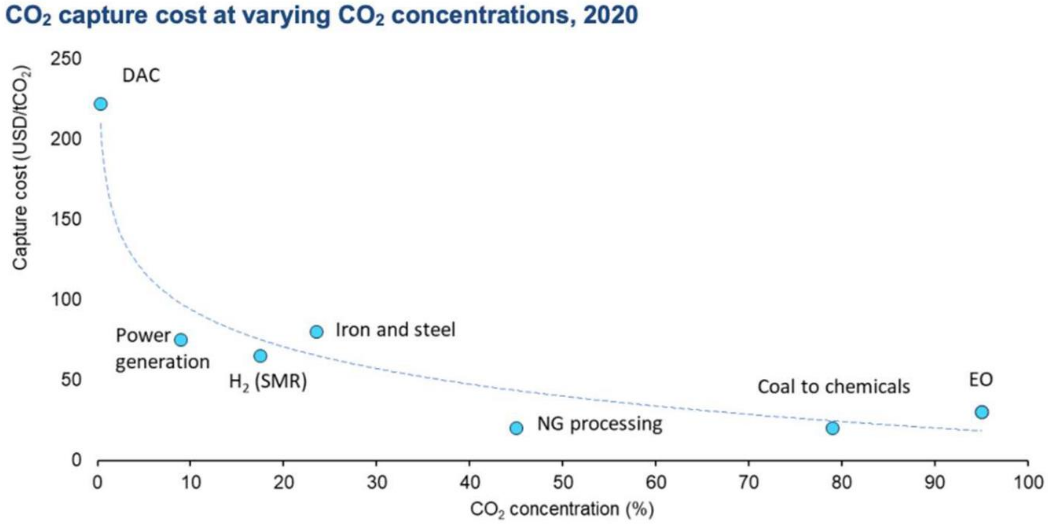
Building on the findings, a spin-off has been launched to support industries in selecting optimal carbon capture technologies and providing expert consulting services. This initiative aims to bridge the gap between academic research and industrial implementation by offering tailored decision-support solutions based on rigorous techno-economic and environmental assessments.

WP2 Power to Chemicals (Metin Bulut, PieterJan Debergh, (VITO))

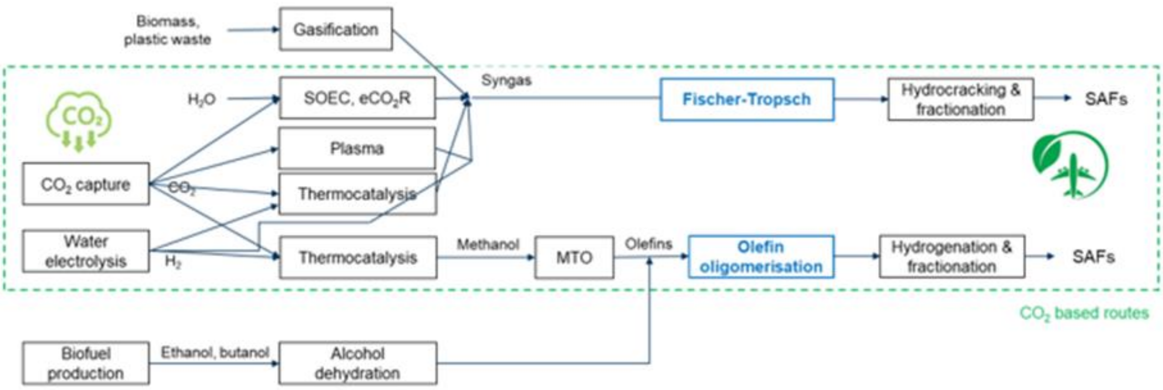
In previous years of PROCURA, WP2 has looked into the economics of the production of various power-to-X applications (methanol, ammonia, syngas). In the final year, insights have been brought together and coupled with the results of WP3 to draft a roadmap with a specific focus on the roll-out of power-to-X and CCU in Belgium. The roadmap is a combination of literature review and an own perspective on the needs to support these technologies in the future. Below, a summary of the insights is provided in the same order as in Deliverable 2.4.

As first part of the roadmap, the basics of Power-to-X has been reviewed. Fundamental concepts are explained, including the distinction between different types of water electrolysers. Alkaline and PEM are relatively mature and used in commercial projects today, while SOEC is in an earlier phase of development but holds significant promise due to its high intrinsic energy efficiency.

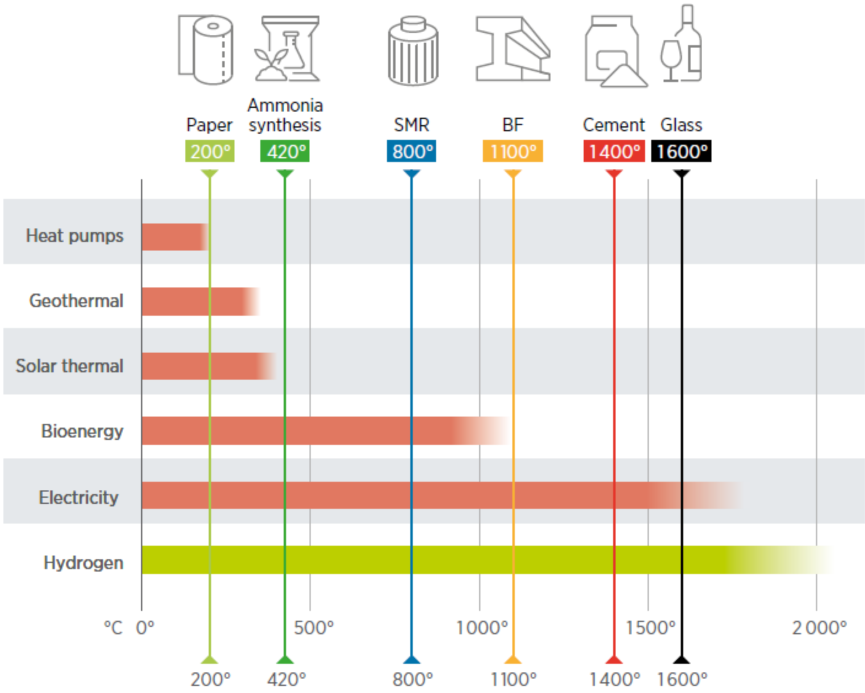
Subsequently, CO_2 sources and capture technologies were briefly reviewed (they are treated in more detail in WP1). It is well known that CO_2 concentration is a critical determinant of capture cost, i.e. CO_2 capture can be relatively affordable for very concentrated sources and becomes quite expensive for less concentrated sources (with the extreme case: direct air capture) as demonstrated in the figure below.



In terms of CO_2 conversion technologies, there are many pathways available, which is illustrated in the figure below which applies to sustainable aviation fuels (SAFs). Usually, to generate syngas a combination of water electrolysis to generate green H_2, and a thermocatalytical process (RWGS) are used, but many alternatives for that are in development, including low and high temperature electrolysis (eCO_2R and SOEC, respectively) and plasma. Apart from the syngas + Fischer-Tropsch route, also the route that runs over methanol has gained attention recently. CCU pathways are in competition with biofuels, which generally have lower cost.



Hydrogen is a versatile but also valuable molecule, and the applications for which it should be used for primarily is a topic of debate. It is currently actively used in refineries for hydrotreating and hydrocracking, but that role will likely decline over time. It is also required to produce molecules such as methanol and ammonia, which is a certain and growing application. Furthermore, to decarbonise steel production, H_2 can be used as reductant instead of CO derived from coal, which will form a significant driver for H_2 demand in the future, provided the sector which is currently struggling with overcapacity can successfully make the transition. More debatable is the role of H_2 to provide heat (see figure below). For low temperatures, many options are available, while for very high temperatures H_2 may play a role. A big question here is how technologies for electrical heating will mature over time.



It is generally acknowledged that direct electrification will play a key role in reducing CO_2 emissions, nevertheless for specific cases such as in industry and (long distance) transport power-to-X may be required. Furthermore, CCS is required to mitigate CO_2 emissions especially in scenario's where little renewable energy is available (see also WP3).

The current situation for PtX and CCU was discussed next in the report. Belgium first unveiled its national hydrogen strategy in 2021, emphasising that electrification should remain a priority wherever techno-economically possible, but as Belgian energy demand is expected to surpass local renewable energy production, electricity and hydrogen molecules import will also play a major role in the country's decarbonisation. The 4 pillars of the strategy are briefly explained below.

1. Positioning Belgium as an import and transit hub for renewable molecules in Europe: The federal government has identified 3 major routes for this – the North Sea route, coordinating with other countries in the North Sea region to synchronise the development of offshore electricity and hydrogen networks; the Southern route, involving the import of hydrogen from southern Europe and northern Africa in the long run; and the shipping route, with hydrogen derivatives imported via ships from diverse locations. Progress towards realising these routes has been in the form of recent agreements being signed with Oman, Namibia and Chile, etc.

2. Expanding Belgian leadership in hydrogen technologies: The federal Belgian government targets expanding the leading position of Belgian companies and research institutions in H_2-molecules and H_2-derivatives research, via initiatives like 'Belgian Energy Transition Fund', 'Clean Hydrogen for Clean Industry' and 'Clean Hydrogen to Belgium'. Although Belgium's focus is more on developing itself as a green hydrogen import hub, it is still targeting setting up a minimum domestic strategic electrolysis capacity of 150 MW by 2026.

3. Establishing a robust hydrogen market: The Belgian federal government has proposed investigating together with the Regional governments and the European Commission how best to put in place a system to unlock the demand for renewable H_2-molecules and H_2-derivatives. Belgium has adopted a Hydrogen Act to develop, by 2026, 100 to 160 km of additional hydrogen pipelines to be operated under non-discriminatory third-party access conditions. This network is to be extended by 2030 to connect the ports of Zeebrugge, Ghent and Antwerp to industrial zones and neighbouring countries.

4. Investing in cooperation as a key success factor: Successfully developing a hydrogen economy in Belgium will require intra- and international cooperation. At the intra-national level, the required cooperation is between the federal and regional governments, as well as companies, research institutions and universities, while at the international level, European and broader collaboration is an obvious necessity.

The Belgian federal government expects 30-60% of the demand in molecules in 2050 to be satisfied by hydrogen, with the rest being divided among the different hydrogen derivatives. Given a projected domestic demand of 125-200 TWh of hydrogen and hydrogen derivatives in 2050, this means a demand between 50 and 140 TWh for hydrogen derivatives. Several domestic projects were announced to meet a part of this demand. The North-C-Methanol project in Ghent aimed to capture 65,000 tons of CO2 from industrial point sources to produce 44,000 tons of methanol annually, but now only plans to generate 10,000 tons of green hydrogen annually. Other projects like 'Power to Methanol' in Antwerp and 'Columbus' in Wallonia have been scrapped due to unfavourable market and regulatory conditions. Some blue hydrogen and CO_2 transport projects do remain active, such as the Rodenhuize blue hydrogen project and the Antwerp@C CO_2 project to transport CO_2 by ship or pipeline to the North Sea or the Netherlands.

Given the overall concerning situation regarding PtX and CCU deployment, the TIMES energy system model from WP3 was then used in the report to evaluate the road ahead for these technologies in Belgium. It is found that the future PtX and CCU scenario in Belgium will largely be an extension of the present. Due to limitations in domestic renewable energy availability, green molecules are likely to be imported, but the large quantity of hydrogen that is projected to be imported by Belgium in the coming decades may prove hard to come by, with green hydrogen expensive and scarce and blue hydrogen facing barriers related to CCS availability and public acceptance. Agreements for green and blue hydrogen supply with countries outside Europe may help here. On the demand side, further measures to incentivise the adoption of green molecules are necessary. For example, given the recent hesitation of steel majors to commit to green steel investments, measures such as carbon contracts for difference and creating lead markets to guarantee demand might be needed. As Belgian markets are relatively small, such steps will have to be taken in coordination with other EU countries.

WP3 Power-to-x and CCU within the Belgian situation under several long term scenario's (Joris Valee, Juan Correa Laguna, (VITO))

Context

In Belgium, wind and solar PV today are already cost-competitive and are projected to become the most economical energy sources by 2025. However, recent increases in investment costs and supply chain challenges for wind and solar PV technologies require a renewed focus on overall cost-effective energy systems to reduce fossil fuel reliance and CO_2 emissions. This shift coincides with discussions on the phase-out of Belgium's existing nuclear capacity, increasing the urgency to ensure a stable, secure electricity supply through renewable alternatives.

To support Belgium's decarbonization goals, Power-to-X (PtX) and Carbon Capture, Utilisation, and Storage (CCUS) are seen as essential components. PtX enables surplus renewable energy to be converted into various energy carriers (e.g., hydrogen, synthetic methane, and chemical feedstock), which can contribute stabilising the electricity grid and support clean molecule production. When combined with CCU, PtX offers additional decarbonisation potential.

The PROCURA project aims to develop a quantitative roadmap for PtX and CCUS in Belgium. By engaging stakeholders from industry, technology, and energy sectors, the project seeks to provide actionable insights and accelerate the transition to a low-carbon energy system. Challenges persist, particularly in hydrogen and clean molecule production, where initial cost projections have proven overly optimistic. Economic and geopolitical disruptions from COVID-19, the war which Russia started in Ukraine, rising material costs, and competing decarbonisation strategies (e.g., nuclear energy and CCUS) add further complexity to the future energy roadmap.

The TIMES-BE model is used to draft the PtX and CCUS (molecules) roadmap. The model can represent the full value chain from the import or mining of energy and material resources up to meeting final demands, either energy or products (e.g.: ammonia, glass, space heating, lighting). Full documentation of TIMES-BE can be found on the EnergyVille website PATHS2050.

Summary of the main results:

The fifth and final year of the PROCURA project we have focused on two main activities, which are reflected across the different subtasks in WP3. The first set of activities consists out of updating the TIMES-BE model with latest techno-economic insights and available datapoints such as a cryogenic carbon capture technology in combination with oxyfuel combustion used in non-metallic minerals sector (e.g. cement production). But also, an ethane steam cracker technology, ethanol dehydrogenation used in the chemical sector to make olefins besides selected other technologies and fuels in various sectors.

The focus however was placed on finalizing the PROCURA TIMES-BE scenarios following a method where we have analysed the long-term role of Power-to-X and carbon capture, using over 80 sensitivity parameters. These parameters cover investment costs for various technologies across Belgian energy sectors, including industry, transport, power, and fuel manufacturing. They also consider imported energy sources, storage facilities for hydrogen and CO_2, and relevant policy assumptions. The output of all these runs have been categorized and grouped together. Next, we developed storylines where the main drivers of the energy system such as availability of renewable energy sources, energy vector imports, carbon capture potential, national and EU legislation, social adaptation etc. were evaluated. These have been benchmarked with existing studies and reports from industry, academia and governmental bodies as well presented and discussed with the PROCURA Project consortium. The final result are four scenarios named; EVOLUTION, ACCELERATION, AMPLIFICATION and TRANSFORMATION, which assumptions and results are briefly described as part of this report and more elaborated as part of a separate report which will be made available with the FOD and the public.

Project achievements towards the objectives

Task 3.1 Power to Heat. (VITO, KUL, Waterstofnet)	Defining the application fields of heating by electrical solutions
Task 3.2 Power to mobility P2M. (VITO, KUL, Waterstofnet)	Production of synthetic fuels will be evaluated for different transport modes.
Task 3.3 Power to industrial processes. (VITO, ULiege)	Screening of novel technologies is under development allowing to eliminate the use of fossil fuels: steel based on electrolysis or hydrogen, syngas production using CO2 and electricity.
Task 3.4 Power to energy for dealing with intermittency of renewable energy supply. (VITO, ULiege)	Benchmark Power to X with other seasonal storage options.
Task 3.5 Developing low carbon scenarios with the updated model. (VITO, KUL, waterstofnet, ULiege)	The potential of the new technologies model will be evaluated by developing low-carbon scenarios with a horizon to 2050.

Task 3.1, Power to Heat

Note: for ease of reading, start with chapter *Task 3.5, Developing low carbon scenarios with the updated model*.

Power-to-heat solutions are emerging as a vital strategy for the decarbonisation of industry and buildings, facilitating the integration of renewable energy while diminishing reliance on fossil fuels. Electrification through heat pumps and electric boilers, paired with thermal energy storage, enhances grid flexibility by optimising energy consumption according to renewable availability. By 2040, the electrification of the residential sector could see the deployment of 2 million heat pumps, while commercial heat pump installations may range between 10,000 and 30,000. In industry, electrification will initially be adopted in low- and medium-temperature processes (e.g.,

food and paper sectors), expanding to high-temperature applications (e.g., steel finishing, naphtha cracking) as we approach 2050 and climate policies tighten.
The transition follows a sectoral progression, beginning with residential and agricultural sectors, and subsequently extending to commercial and industrial sectors. While heat pumps drive gains in energy efficiency and cost savings, industrial electrification contends with higher production costs—ranging from a 60% to 300% increase—though some industries may benefit from by-product valorisation. Ultimately, widespread heat electrification, bolstered by building renovations, district heating, and policy incentives, will be crucial to achieving net-zero emissions in Belgium by 2050.

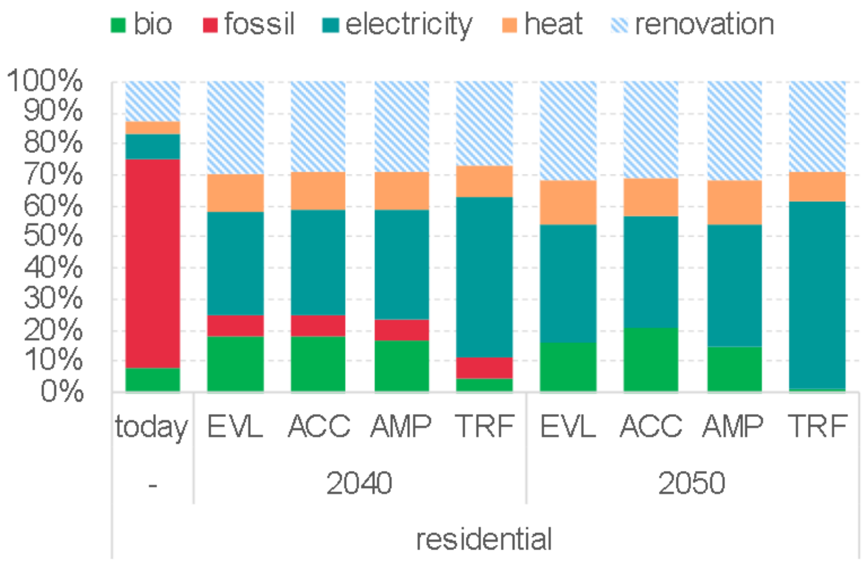


Figure WP3-1: Heat source shares across all sectors per scenario

Conclusion
The electrification of heat follows a sectoral progression, occurring first in residential and agricultural sectors before expanding to commercial buildings and industry. In all cases, the adoption of heat pumps results in energy efficiency gains and cost savings. However, in residential buildings, widespread deployment must be accompanied by building renovations and stringent energy performance standards for new constructions.
In the agriculture sector, biomass-based CHPs provide both heat and electricity, offering grid flexibility as dispatchable energy sources. Similarly, in the commercial sector, CHPs play a significant role in heating, though by 2050, high electrification and district heating are expected to dominate the heat supply.
In industry, low-temperature heat electrification via heat pumps becomes viable around 2030, with further electrification accelerating after 2040 due to rising CO_2 prices, expanded low-carbon electricity capacity, and climate targets. While this transition may lead to higher production costs—averaging 60% and up to 300% in some cases—certain industries may benefit from reduced production costs and enhanced by-product valorisation, highlighting the complex economic dynamics of industrial decarbonisation.

Task 3.2, Power to Mobility

Note: for ease of reading, start with chapter *Task 3.5, Developing low carbon scenarios with the updated model*.

Direct electrification through EVs, supported by smart charging and V2G, can enhance grid flexibility by aligning charging with renewable generation and potentially feeding electricity back into the grid during peak demand. Indirect electrification, through hydrogen production via electrolysis, offers additional storage and flexibility by converting surplus renewable electricity into clean fuels such as e-methanol and e-kerosene. By 2050, these strategies are expected to improve renewable energy penetration, enhance grid stability, and reduce curtailment of excess wind and solar power.
In all scenarios, road transport is fully electrified by 2040, leading to a 75% reduction in final energy consumption. Smart charging and V2G technologies significantly contribute to accommodating large volumes of renewable energy. However, local hydrogen production from renewables proves costly, as Belgium faces limited availability of low-carbon, affordable electricity. Consequently, direct electricity use is prioritized, while hard-to-electrify sectors—such as aviation

and maritime shipping—will rely on imported synthetic fuels (e.g., ammonia, e-methane, e-kerosene).
Full electrification of road transport will require substantial infrastructure investments in charging networks and grid expansion. Meanwhile, as clean fuels and synthetic molecules will remain essential for certain sectors, strategic import agreements and infrastructure development at airports and seaports to secure future energy supply are essential.

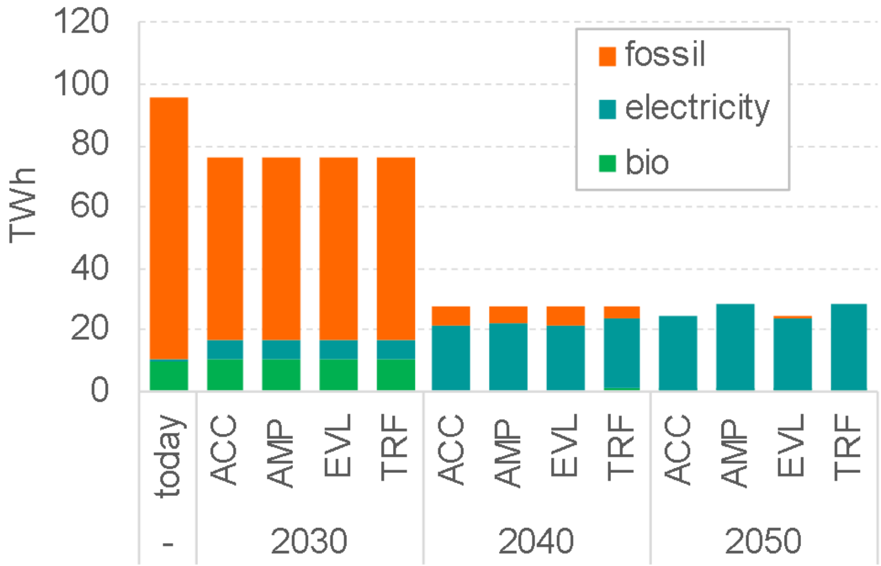


Figure WP3-2: Final energy consumption per vector across all mobility sectors, per scenario

Conclusion
After 2030, road transport in Belgium will be fully electrified, drastically increasing the need for infrastructure (e.g. public and private chargers, distribution grid). The integration of smart charging and V2G technologies will not only enhance grid flexibility but also facilitate the large-scale integration of renewable energy, minimizing curtailment and supporting power generation during peak demand periods.
While local hydrogen production from renewables remains costly under the explored scenarios, direct electricity use is prioritized due to the limited availability of low-carbon and affordable electricity in Belgium to produce large volumes of hydrogen and synthetic fuels. However, synthetic fuels and clean molecules will still play a critical role in decarbonizing sectors where electrification is not feasible or more difficult, such as maritime shipping and aviation. These fuels will primarily be imported, therefore importing infrastructure and agreement with synfuel providers will be fundamental for important assets such as airports and seaports.

Task 3.3, Power to Industrial processes

Note: for ease of reading, start with chapter *Task 3.5, Developing low carbon scenarios with the updated model*.

As CO_2 prices rise and free allowances decline, industries are expected to transition toward low-carbon production methods. While hydrogen will play a role, direct electrification is emerging as a key alternative, particularly for low- and medium-temperature heat through heat pumps, electric boilers, and thermal storage. For high-temperature heat, electric furnaces and hybrid electric-gas systems could replace fossil fuels, while electrochemical technologies may enable cleaner chemical and fuel production.
By 2050, electricity and biomass will account for nearly 40% of industrial energy use, yet full electrification remains challenging, with fossil fuels still supplying 60% of final energy demand. Low-temperature heat is expected to be fully decarbonized by 2035, but high-temperature processes may rely on CCUS instead of full electrification. Strategic policy support, infrastructure investment, and innovation will be critical in driving industrial electrification, ensuring a smooth transition to a net-zero future.

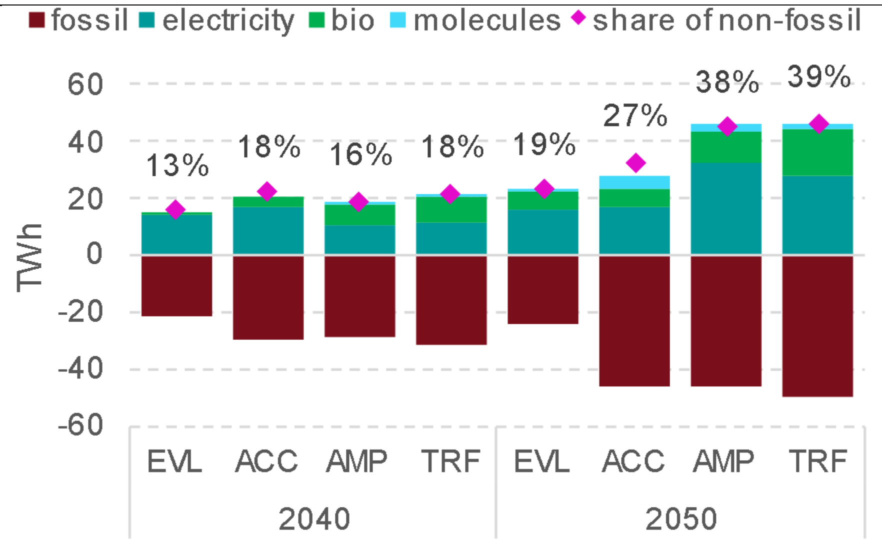


Figure WP3-3: Energy variation compared with today per vector, across all industrial sectors, per scenario

Conclusion

The electrification of low-temperature heat should be actively promoted in the near future, facilitating the widespread adoption of heat pumps in industry. Conversely, the electrification of high-temperature heat will depend on guaranteeing a reliable energy supply and affordable electricity prices to make it a feasible option for industrial applications. Furthermore, the uptake of disruptive full-electric and electrochemical production technologies will necessitate targeted incentives and policy mechanisms to enhance their cost competitiveness. The successful deployment of these solutions will rely on strategic investments in infrastructure, regulatory support, and ongoing technological innovation, thereby ensuring a smooth transition towards a net-zero industrial sector.

Task 3.4, Power to Energy for dealing with intermittency of renewable energy supply

Note: for ease of reading, start with chapter *Task 3.5, Developing low carbon scenarios with the updated model*.

The integration of wind and solar PV in Belgium's energy system requires solutions to address their seasonal variability and intermittency. Dispatchable capacity and long-term storage will be essential to balance supply and demand. Power-to-energy technologies, such as hydrogen and clean molecules, can store excess renewable electricity and serve as backup when generation is low.

By 2050, short-term storage—particularly stationary batteries (4–7 GW) and vehicle-to-grid (V2G) technology (0.6 GW)—will play a more dominant role than molecule-based alternatives. Clean-molecule power plants will be used mainly during demand peaks, with installed capacity reaching 2–5 GW depending on the scenario. However, their low utilization requires strong incentives. Belgium's transition will rely more on European grid integration than on large-scale seasonal storage. Imports of clean molecules will complement short-term storage to manage seasonal demand variations, supporting a flexible, low-carbon power system while reducing dependence on fossil-based backup generation.

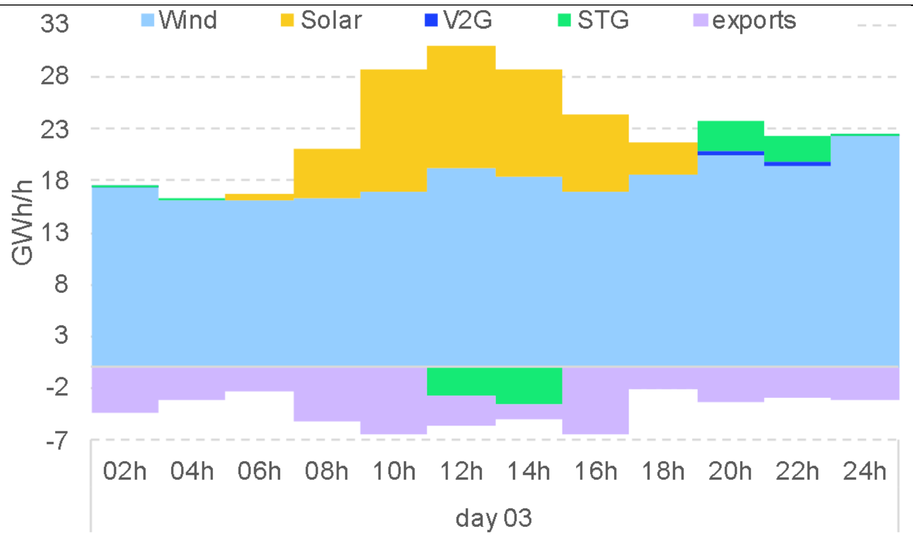


Figure WP3-4 Dispatch of wind, solar, imports electricity, exports electricity and storage for one representative day in the year.

Conclusion
Seasonal storage is expected to play a limited role in Belgium's energy transition, as the country moves toward a more integrated European power system, where cross-border electricity trade provides a key source of seasonal flexibility. Similarly, clean molecules will have a limited but essential role in the power sector, primarily as backup technologies. However, their low utilization factor necessitates strong economic incentives to ensure viability. To address seasonal demand variations, molecule imports will likely become an important complement to short-term storage solutions, helping to smooth residual demand fluctuations and enhance grid stability.

Task 3.5, Developing low carbon scenarios with the updated model

The PROCURA scenarios

The exploration of several future energy system scenarios provides insights as standalone cases or by contrasting results among them. However, scenario development can be a tedious task due to data availability, stakeholder inputs, long time horizons and computational demand, to name a few. This can quickly lead to a multitude of scenarios, which can clutter an interesting discussion of the model results. Therefore, we decided to limit the number of scenarios to four. As the definition of a central scenario can be ambiguous and not consensual, there is no dedicated reference scenario. Conversely, each scenario serves as a reference case based on what one considers to be most aligned with one's future vision. The four scenarios are:

EVOLUTION (EVL):

In this scenario, the price of CO_2 continues to rise to 480 €/ton. Natural gas prices are expected to remain relatively stable at 31 €/MWh by 2050. International aviation and maritime will reduce CO_2 emissions by 70% and 100% respectively. In 2035, hydrogen imports via pipeline will take off with a maximum net import capacity of 0.5 GW and up to 1.5 GW by 2050. Additionally, import terminals for low-carbon molecules are expected to be deployed starting in 2030. Furthermore, semi-finished products based on molecules, such as ammonia and sponge iron, will be traded, making them potential import options from 2035. It is expected that Belgium will have access to an additional 8 GW of far offshore wind in the North Sea (E.g in the Dutch or Danish Exclusive Economic Zone), besides 8 GW near its coast. However, the High Voltage Direct Current (HVDC) electricity grid rollout will slowly reach a maximum of 4 GW by 2050 due to social and regulatory factors. New nuclear Generation III (GENIII) is available from 2040 at 9220€/kW, and new nuclear Small Modular Reactors (SMR) as of 2050 at a similar cost as GENIII but with higher flexibility. However, the total Belgian nuclear capacity is limited to 4 GW.
Due to potential public opposition, solar PV is limited to 40 GW and wind onshore to 10 GW. Moreover, participation and technology adoption from households are not absolute, with a

lower uptake of maximum 70% of domestically installed heat pumps by 2050, Electric Vehicles (EV) participating in vehicle-to-grid (V2G), and smart charging will reach 14% and 13% respectively.

ACCELERATION (ACC):

Conversely to EVOLUTION, hydrogen infrastructure across Europe is deployed faster, with a net H2 pipeline import capacity increasing up to 1.5 GW and 3 GW by 2035 and 2050 respectively. Simultaneously, molecule import prices decrease as global production increases faster. On the other hand, nuclear SMR is available at a large scale and 5 years sooner, starting in 2045. While focusing on nuclear and molecules in the ACCELERATION scenario, Direct Air Capture (DAC) is not made available to the model at large scale and CCS facilities are limited which keeps CO2 storage costs high at 100 €/tCO2.

AMPLIFICATION (AMP):

In this scenario, hydrogen import infrastructure will be larger (5 GW) by 2050. However, although global demand for molecules increases rapidly, it is not expected that prices will be any different. Moreover, nuclear GENIII is now available in 2045 at the same cost as nuclear SMR. Carbon storage remains highly competitive in Europe, hence, 10Mta is expected to be the maximum for Belgium by 2050. Solar PV and wind onshore can go to their maximum potential of 104 GW and 20 GW, smart charging vehicles are heavily incentivized up to 48%, Vehicle to Grid (V2G) participation increases to 38% and financial and technical hurdles are sorted out to unblock domestic heat pump adoption. To support this transition, Belgium increases its access to far offshore wind, from 8 to 16 GW, without limits to HVDC infrastructure. Furthermore, the import of biomass will increase by 14 TWh/yr by 2050. Finally, the import of semi-finished products is more difficult due to regulations and policies, targeted to keep industrial activities in Belgium.

TRANSFORMATION (TRF):

This scenario sees a revolution in the molecule market which is characterised by lower molecules import prices, cheaper electrolysers and 5 GW of net-import pipeline hydrogen capacity by 2050. CCS is expected to reach a maximum of 10Mta by 2050. As natural gas prices go up due to market effects, geopolitical tensions and EU/Belgian policy revisions, there is an effort to make the installation of nuclear SMR available sooner, starting in 2040, intending to support 16 GW of far offshore wind dedicated to Belgium. In this context, flexibility is promoted by vehicle smart charging up to 70%, V2G up to 72% and faster domestic heat pump deployment. In this scenario, the industry is supported by regulatory bodies, making the import of semi-finished products impossible.

General results

The four scenarios reach decarbonisation as this is a constraint of the model. Nevertheless, the trajectory to 2050 is different (see Figure 3) and implies different cumulative CO2 emissions, energy mix and costs. The reduction of emissions depends on four main strategies which are electrification, clean molecules, carbon capture and bioenergy. Figure 4 shows the trajectory of the most important parameters which provide a glimpse of the behaviour of each one in each scenario.

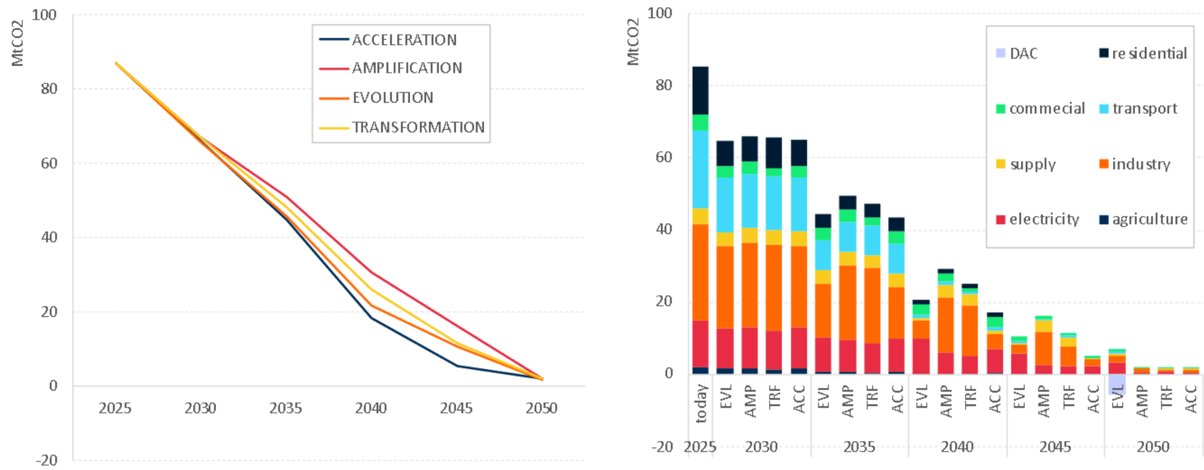


Figure WP3-5 CO2 emissions trajectory by scenario.

Belgium follows a decarbonisation trajectory, reaching net-zero by 2050 in all the cases as this is imposed as a target in the model. Nevertheless, the transition period between 2035 and 2045 is different in each scenario. ACC shows a faster decarbonisation trajectory as it counts with more low-carbon electricity sources. Final energy consumption is projected to decrease by 20% between 2040 and 2050. Electrification of demand occurs across all scenarios, although the pace of implementation varies. The use of natural gas declines steadily as it is increasingly replaced by electricity and bioenergy, with alternative molecules playing a more limited role. CCUS becomes very important in the decarbonisation strategies of some sectors such as cement, lime and steel, leading to captured volumes around 13-30 MtaCO2.

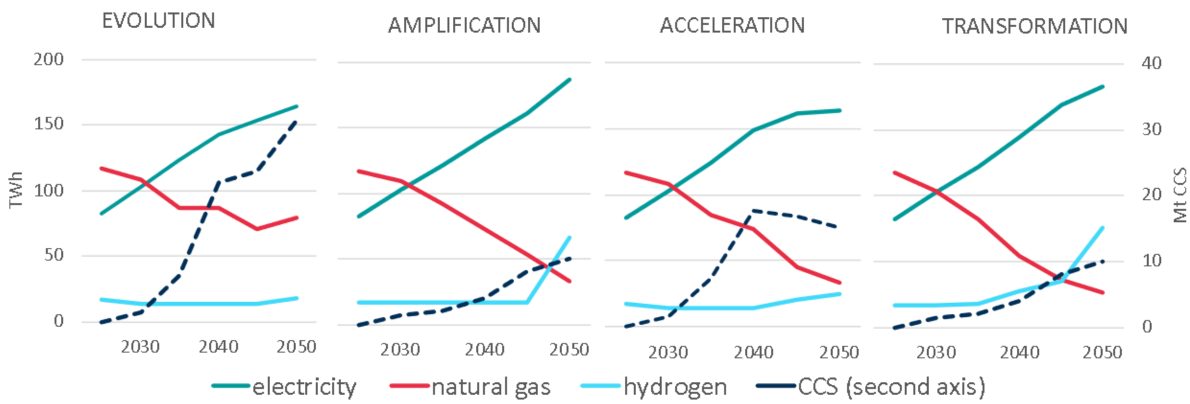


Figure WP3-6 Trajectory of final electricity, natural gas and hydrogen energy and non-energy consumption, as well as carbon capture and storage.

Final energy consumption is projected to decrease by 20% between 2040 and 2050, followed by a slight increase toward 2050 due to the adoption of energy-intensive carbon capture technologies. While electrification of demand occurs across all scenarios, the pace of implementation varies. The use of natural gas declines steadily as it is increasingly replaced by electricity and bioenergy, with alternative molecules playing a more limited role. In this context, hydrogen demand remains moderate, with a notable surge only in the APLIFICATION and TRANSFORMATION scenarios, where industrial hydrogen consumption rises sharply by 2050.
There is an increase in final energy consumption due to CCS, ranging from 1% to 3% of total final energy consumption, this is around 4-14 TWh. CCUS becomes very important in the decarbonisation strategies of some sectors such as cement, lime and steel, leading to captured volumes around 13-30 MtaCO_2. Considering the energy consumption and the captured CO_2, the energy intensity of this technology will be around 0.5 MWh/tCO_2, which could be 50-100% electrified.

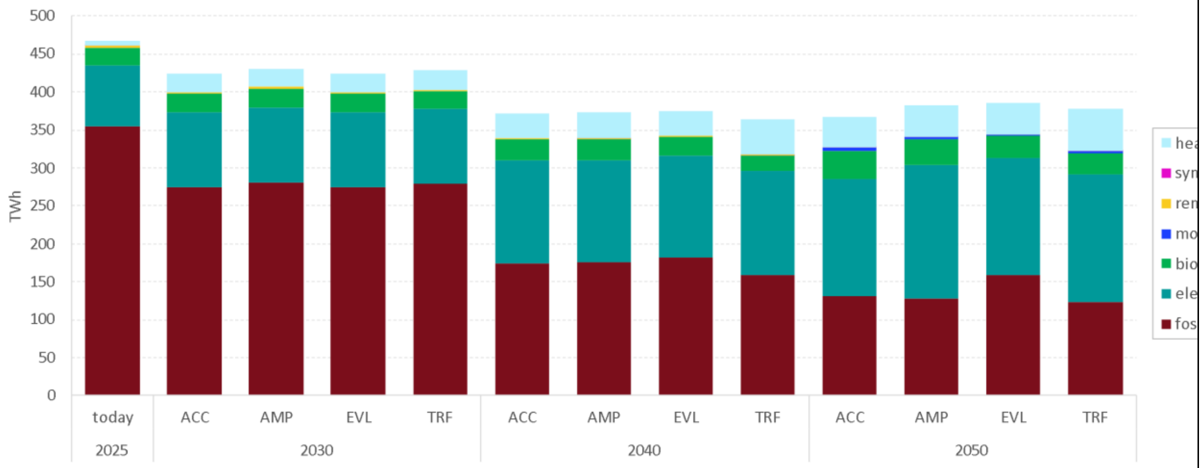


Figure WP3-7 Final energy and non-energy consumption per scenario

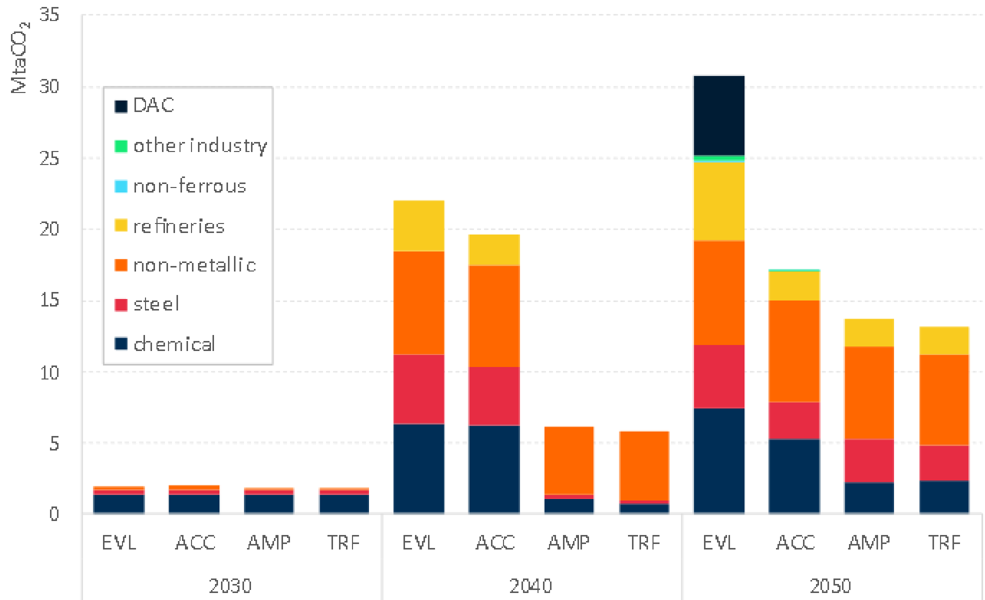


Figure WP3-8 Carbon capture per sector and scenario

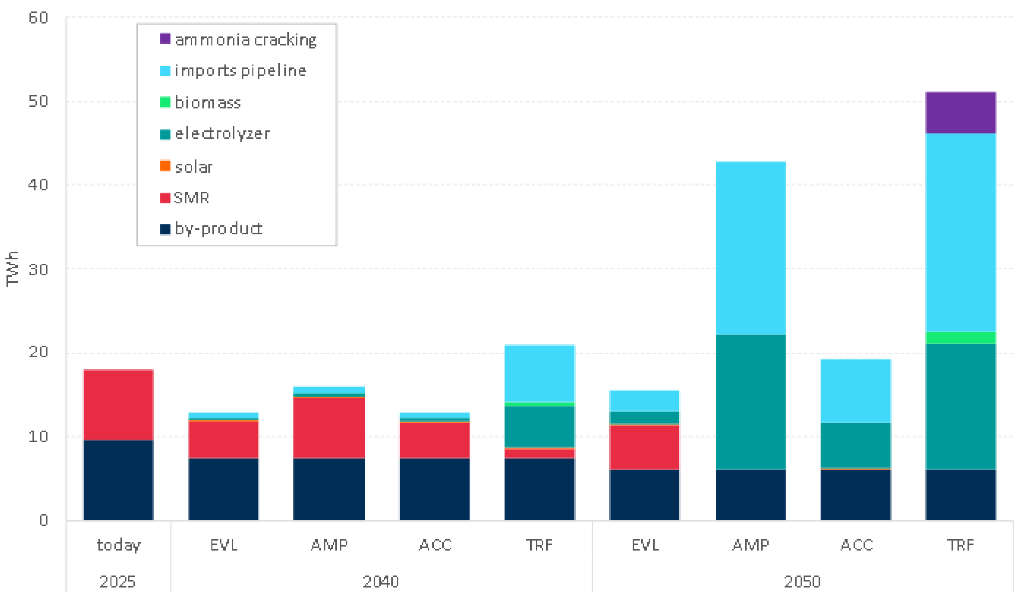


Figure WP3-9 Hydrogen production per source and scenario

WP4 Solar fuels (Maarten Houllebergh (KUL), Tom Aernouts (imec))

Solar fuels - Summary of the main results (KUL)

Within the PROCURA project, KU Leuven was responsible for mapping, analyzing, and contextualizing emerging solar fuel technologies — that is, technologies that directly or indirectly convert solar energy into chemical fuels such as hydrogen or hydrocarbons. The work was structured into four tasks (T4.1 to T4.4), covering everything from a broad mapping exercise to techno-economic analysis, trend identification, and integration with other work packages.

T4.1 – Technology Status Assessment (KUL)

In this task, KU Leuven conducted a comprehensive mapping of existing solar fuel technologies. These were classified into four primary categories: solar thermochemical, photobiological, photocatalytic, and photoelectrochemical approaches. For each category, KU Leuven analyzed the underlying principles, technology readiness level (TRL), and current state of development. The assessment included a review of international research initiatives, commercial activities, and pilot-scale implementations. Since the previous update, 3 additional companies/start-ups have seen the light of day which are worth mentioning here: Peregrine Hydrogen (novel electrolyser technology, USA), Brineworks (electrolytic electrodialysis to remove CO2 from seawater while producing hydrogen, Netherlands) and Sora Fuel (novel type of bicarbonate-based electrolyser producing syngas from CO2 and water, which is then converted to SAF through Fischer-Tropsch, Canada).

In addition to the technology mapping, KU Leuven benchmarked the identified solar fuel technologies against conventional water electrolysis. This comparison focused on criteria such as efficiency, cost, scalability, maturity, and suitability for deployment in the Belgian context. The result was a nuanced overview of strengths and limitations for each technology class, forming a foundation for selecting candidate technologies for deeper analysis.

T4.2 – Techno-Economic Analysis of Selected Technologies (KUL)

Following the technology mapping, KU Leuven selected key solar fuel technologies for in-depth analysis based on their potential relevance for Belgium and their projected technological evolution. The main candidates included photoelectrochemical water splitting and solar thermochemical fuel production.

For each selected technology, KU Leuven conducted a detailed techno-economic analysis. This involved identifying process characteristics (e.g. efficiency, materials requirements, energy input), evaluating capital and operational expenditures, and analyzing potential cost trajectories over time. A key insight from this analysis was that while some solar fuel technologies show promising long-term potential, they currently remain less mature and more costly than electrolysis-based approaches.

KU Leuven also performed sensitivity analyses to assess how variations in key parameters — such as solar irradiance, material costs, and system efficiency — would affect the overall feasibility of each technology. The results indicated that while solar thermochemical and photobiological approaches offer unique advantages, such as high energy density fuels or the ability to produce complex chemicals, their large-scale deployment in Belgium is currently limited. This is mainly due to constraints related to land use and the relatively low intensity of direct sunlight in the region. In contrast, photoelectrochemical and integrated PV-electrolysis systems showed strong potential for decentralized hydrogen production in Belgium, particularly when combined with emerging high-efficiency tandem solar cells. These technologies may be well-suited for local energy networks and applications where compact, modular systems are an advantage.

T4.3 – Technology Trends and Future Potential (KUL)

In this task, KU Leuven examined the expected evolution of solar fuel technologies over time, with a particular focus on TRL development and scalability. A SWOT analysis was conducted for each technology class, identifying strengths, weaknesses, opportunities, and threats. This analysis was updated with recent developments from the academic and industrial sectors.

To further illustrate future potential, KU Leuven developed a set of case studies of commercial or near-commercial initiatives. These included:

- **Synhelion (Switzerland)** – building the first industrial-scale solar kerosene plant using thermochemical processes.
- **Photanol (Netherlands)** – piloting the use of engineered cyanobacteria to produce biochemicals from CO_2 and sunlight.
- **Fusion Fuel (Portugal)** – deploying compact integrated PV-electrolysis units using CPV panels and miniaturized PEM electrolysers.
- **University of Tokyo (Japan)** – scaling up artificial photosynthesis using photocatalytic panels for green hydrogen and methane production.

These case studies highlighted the diversity in technological approaches and market applications. They also emphasized that while Belgium may not be suitable for all solar fuel production pathways (e.g. thermochemical systems requiring high solar irradiance), there could still be a role in downstream integration or technology development.

T4.4 – Connection to Other Work Packages and Updating Reports

In the last year of the PROCURA project, KU Leuven focused on translating the knowledge gathered in T4.3 into usable data. In consultation with the VITO team (WP3), a parameter space was defined which should allow for the incorporation of the different solar fuel technologies into the TIMES-BE model used for the different scenarios in WP3. Given the low TRL level of most technologies and the scarcity of available data, an alternative approach was adopted to estimate the different parameters. This approach involved setting up a database of > 80 scientific publications, product and process specification sheets, etc. and feeding this into an AI model. After a series of iterations and extrapolations, a first parameter set was obtained for solar thermochemical, photobiological, photocatalytic and photoelectrochemical solar fuel technologies, factoring in the different process configurations, output products and future improvements. The data was shared with VITO and implemented in the TIMES-BE model. While the data in itself are a good first approximation of the various operational parameters of the different technologies, these values are prone to change as more and more data becomes available in the future. The most relevant parameter sets are shown below (Figures 4.4.1-4.4.3); the full dataset will be made available on the PROCURA website.

Solar Thermochemical SYGNAS output

		2025	2030	2040	2050
CAPEX	€/kW	2500	2200	2000	1800
FIXOM	€/kW-yr.	55	50	45	40
VAROM	€/kWh	0,025	0,022	0,02	0,018
main output (Syngas)	kWh	50	100	150	200
by product	kg (O2)	1,5	3	4,5	6
input 1 (solar radiation)	kWh	1000	1000	1000	1000
input 2 (electricity?)	kWh	3	2	2	1
input 3 (water)	kg	19,3	38,6	57,9	77,1
input 4 (CO2)	kg	47,15	94,29	141,44	188,34
footprint	m2/kW	15	14	11	10

Figure 4.4.1: Parameter set for solar thermochemical technology producing syngas (based on Synhelion case study).

Photobiological lactic acid production (with cyanobacteria)

		2025	2030	2040	2050
CAPEX	€/kW	1800	1600	1400	1200
FIXOM	€/kW-yr.	45	40	35	30
VAROM	€/kWh	0,03	0,028	0,025	0,023
main output (lactic acid)	kWh	10	12,5	15	20
by product	BIOMASS				
input 1 (solar radiation)	kWh	1000	1000	1000	1000
input 2 (electricity?)	kWh	2	2	1,5	1
input 3 (water)	kg	2,03	2,54	3,05	4,06
input 4 (CO2)	kg	3,49	4,36	5,24	6,98
footprint	m2/kW	50	40	30	20

Figure 4.4.2: Parameter set for photobiological technology producing lactic acid (based on Photanol case study).

Photocatalytic (H2 output)

		2025	2030	2040	2050
CAPEX	€/kW	1700	1500	1300	1100
FIXOM	€/kW-yr.	45	40	35	30
VAROM	€/kWh	0,03	0,028	0,025	0,023
main output (H2)	kWh	62	72	82	92
by product	kg (O2)	5,58	6,48	7,38	8,28
input 1 (solar radiation)	kWh	1000	1000	1000	1000
input 2 (electricity?)	kWh	1	1	1	1
input 3 (water)	kg	8	9,3	10,5	11,8
footprint	m2/kW	50	40	30	20

Figure 4.4.3: Parameter set for photocatalytic technology producing hydrogen.

T4.7 Screening of wire and non-wire integrated system of solar cell and compact electrolyzer

In continuation of the experimental set-up described in Task 4.6 and 4.7 in previous years, an advanced novel set-up has been created, whereby the PV cell is much closer integrated with the electrolyzer element.
A whole new design was developed for this, taking into account that electrode connections and other wiring, feedthroughs and piping should no longer be positioned on the front or backside of the electrolyzer element to allow a clean and flat surface to be available to attach the PV module directly on the electrolyzer element. Therefore, connectors etc had to be brought to the sides of the electrolyzer element, as can be seen in the exploded view in Fig. 4.7.1. On the left side, the PV module is depicted, to be attached to the front of the electrolyzer element.

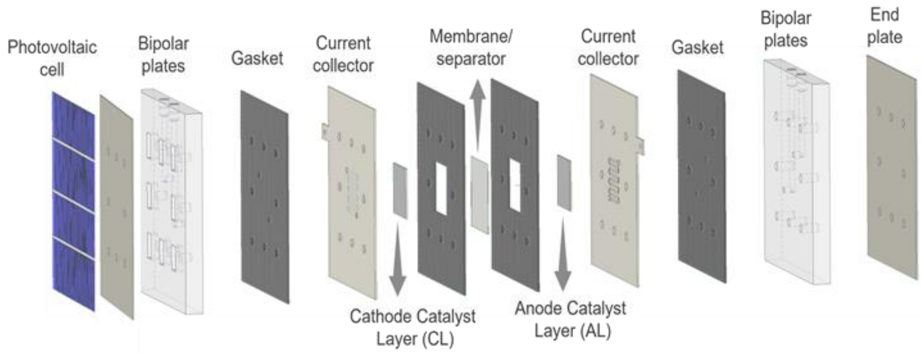


Figure 4.7.1: Exploded view of the novel advanced electrolyzer design; on the left side the PV element is represented, to be directly attached at the front of the electrolyzer

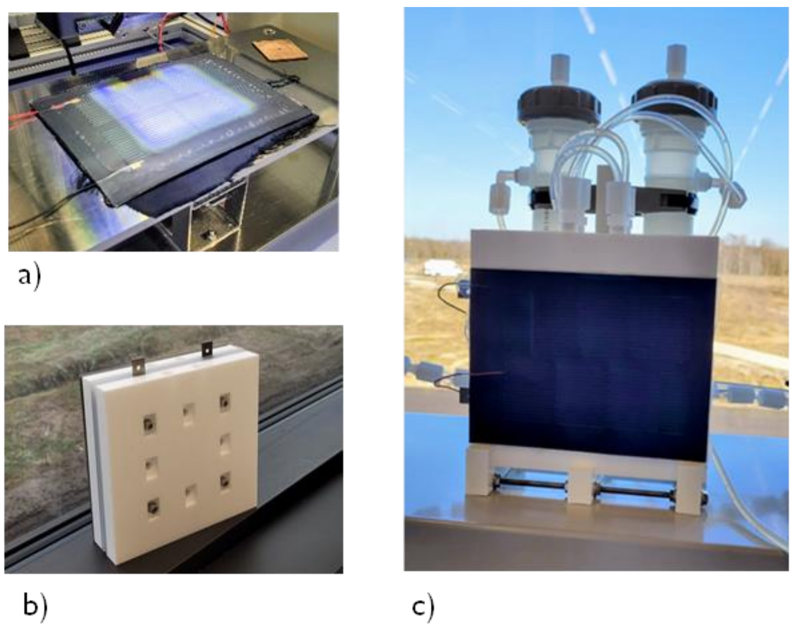
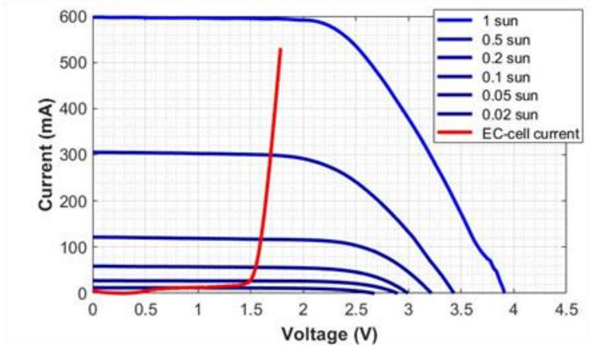


Figure 4.7.2: The PV-integrated electrolyzer realized, with a) the CIGS PV module or test illumination, b) the 20cm by 20 cm newly designed electrolyzer element, and c) the completed assembly

The actual realization of this PV-integrated electrolyzer system is demonstrated with pictures in Fig. 4.7.2. A thin-film, lightweight CIGS solar cell (CIGS = Copper-Indium-Gallium-Sulfur) assembly was selected to act as PV power source (Fig. 4.7.2a). The assembled electrolyzer element is shown in Fig. 4.7.2b, with a size of 20cm by 20 cm. Finally, the fully assembled PV-integrated electrolyzer set-up can be seen in Fig 4.7.2c, whereby the dark blue rectangular surface in the front is the PV module. The vessels at the back are the ones where the oxygen and hydrogen gas are collected.

a)



b)

Figure 4.7.3: a) the PV-integrated electrolyzer set-up under operation with a light source in the front; b) the output curves of the PV module (blue) under different illumination intensities, and of the electrolyzer element (red)

The operation of this PV-integrated electrolyzer system is tested under different illumination intensities, as represented in Fig 4.7.3a. The output curves of the PV module under different calibrated simulated solar light are given in the graph in Fig 4.7.3b, together with the operations curve of the electrolyzer. It can be seen that the electrolyzer can remain operational under a wide range of light intensities, from full 1 sun illumination even down to 0.05 sun.

In conclusion, a close integration of PV solar modules directly coupled with an electrolyzer element has been successfully demonstrated, thanks to an advanced novel design of the electrolyzer element. A broad operational range under different illumination intensities has been realized with this set-up, allowing to reduce impact of variation in solar illumination under real-world operation conditions. This should result in a high amount of effective operational hours in field operation, even when clear sky isn't guaranteed over the whole day, like typical in a climate as we know in Belgium.

WP5 Demonstrator (Joost Helsen, (VITO))

WP6 Comparative analysis other countries (Isabel Francois, Michel Honselaar (Waterstofnet))

The following activities have been done during year 5 of the project:

Task 6.1: Comparison of status, trends, evolutions in neighbouring countries

In this task, a continuous monitoring of hydrogen developments, announcements and strategies is done for the neighbouring countries, the EU and some specific locations outside the EU.

In year 4 we have provided a deliverable with all data until the date of the report.

In year 5 we have continued to monitor the most import countries and publications. We have integrated these results in the deliverable 6.2, where we made an extensive analysis of the international state of play and developed a tool to assess countries on their potential to collaborate with Belgium for importation of hydrogen

Task 6.2: Mapping of activities & perspectives for Power-to-X in countries with low-cost renewables
In this task, non-EU countries that have a potential to supply hydrogen and/or derivatives to Belgium are identified. In year 5, we have summarized all the knowledge we have gathered during this project in an extensive deliverable 6.2 with:

- A thorough **literature study** on all aspects of importation of hydrogen from countries with low cost renewables (techno-economic aspects but also geopolitical and social aspects). Institutes as Irena and the Hydrogen Council (studies done by McKinsey) have developed tools to calculate hydrogen production costs (example figure WP6-1 & WP6-2) all over the world and have developed models to describe hydrogen trade flows between countries and continents(see visualization figure WP6-3).
- The description of a few **existing tools** that have been developed to assess the potential of countries for collaboration w.r.t. hydrogen and -derivatives importation.
- The description of a **new tool** we have developed ourselves within this project to do this assessment. In first instance, we have used a very extensive list of criteria (worked out within a student project under supervision of WaterstofNet). The result of that exercise, based on the current scoring of the 5 categories of criteria with in total more than 70 single criteria, is shown in figure WP6-4.
- As a last step, we have simplified the tool again down to 24 criteria, for which public data are available with regular updating (e.g. through Worldbank; World population review, theglobaleconomy etc…)
- As a conclusion, we have listed the different MOU's and described the main developments of BE companies in a number of the 'MoU countries'. Activities of BE companies in specific countries, often based on historical relations, define the attractiveness for developing H2 activities in these countries. Therefore, the 'gut-feeling' list of top countries generated by the Belgian Hydrogen Council members, differs from the assessment tool results (cfr Figure WP6-5).
  And the world is changing rapidly.
  Since this high level assessment at the end of 2023, other new champions as Brasil and India have entered the arena, offering new opportunities for both export of hydrogen and investments in technology manufacturing.

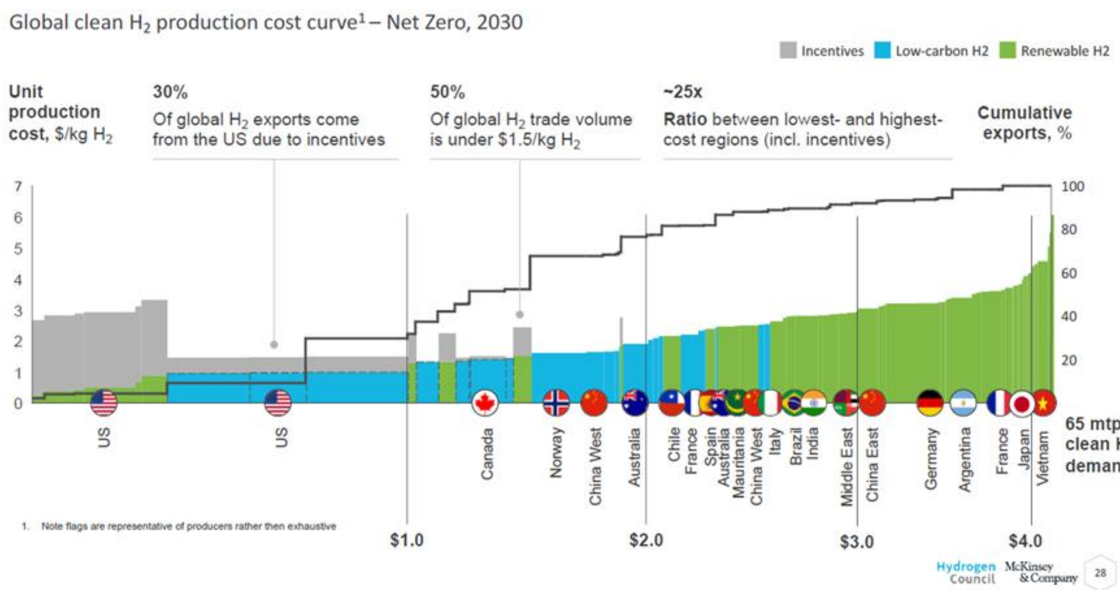


Figure WP6-1:Estimated cost for hydrogen production, including the effect of incentives, from Hydrogen Council publication.

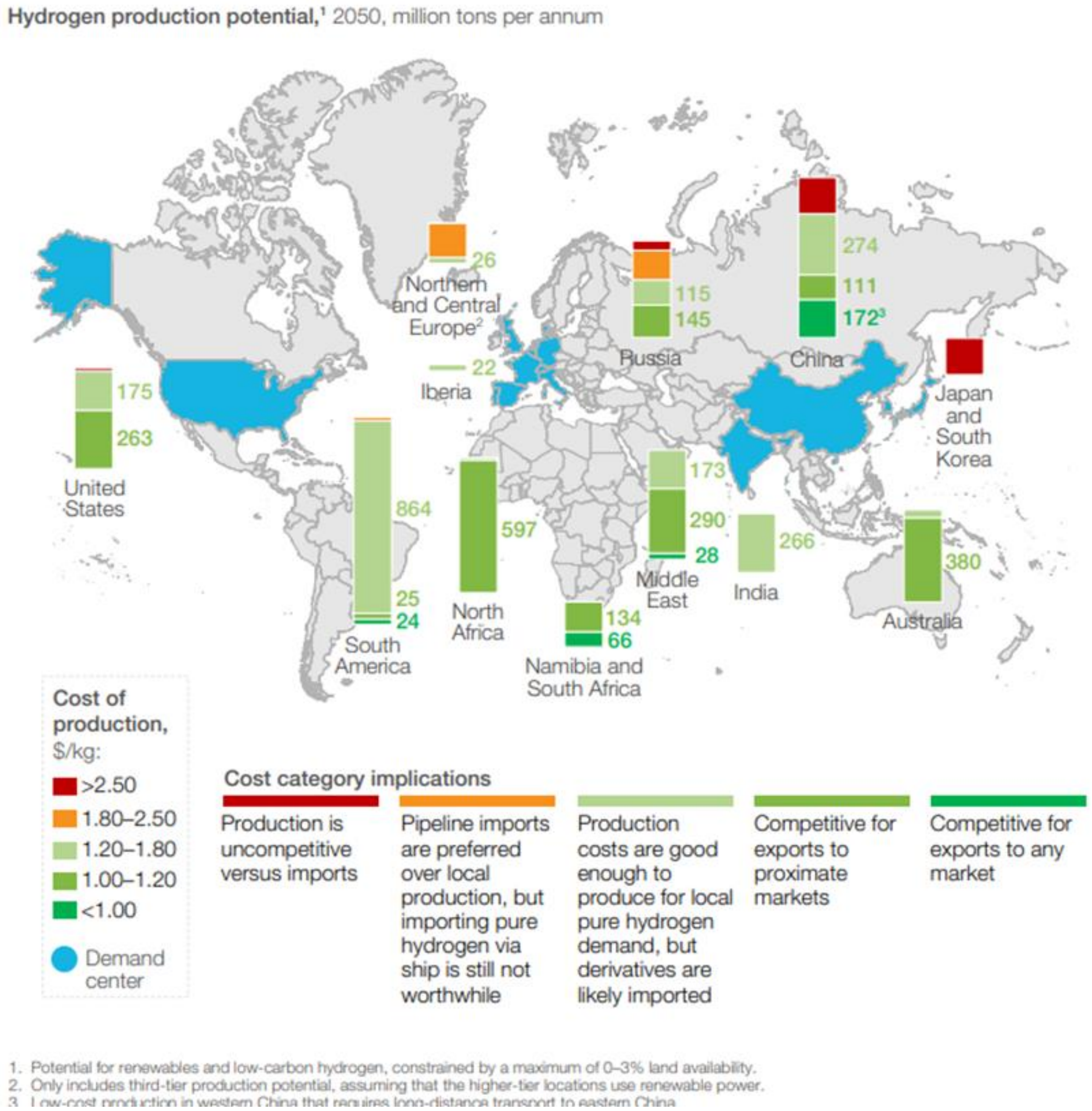


Figure WP6-2: Production potential and estimated cost for hydrogen production in different parts of the world and categorisation of the countries w.r.t. their import/export status (source Hydrogen Council).

Figure WP6-3: Trade flows as modelled by the Hydrogen Council, based on a minimal cost approach.

Main Overview

Country	Sum of Technical criteria score	Sum of Economic criteria score	Sum of Social criteria score	Sum of Environmental criteria score	Sum of Geopolitical criteria score
United States of America	81%	69%	79%	31%	75%
Canada	81%	63%	85%	32%	87%
Australia	81%	60%	82%	33%	89%
Chile	80%	55%	58%	41%	77%
United Kingdom	79%	60%	81%	45%	82%
Spain	77%	59%	76%	39%	83%
Oman	67%	61%	57%	40%	47%
Brazil	64%	46%	65%	31%	48%
Egypt	61%	41%	52%	27%	22%
Namibia	57%	48%	49%	53%	67%
India	57%	50%	47%	28%	42%
Morocco	56%	52%	53%	39%	44%
Mauritania	45%	46%	45%	46%	33%

Filtered on technical scores

→ Western countries overall better conditions, except for environmental

Figure WP6-4: Result of the assessment of a large number of countries along a list of 5 different categories of criteria, resulting in the most interesting countries for future import of hydrogen

Technical	Economic	Social	Environmental	Geo-political
(TI1) # Full load hours renewable energy wind & solar (hydro or geothermal)	(EI1) Credit rating	(SI1) Government expenditure on education, total (% of GDP)	(EVI1) Environmental Performance Index (Score 0-100):	(GPI1) Political Stabil Index (-2,5 for lowest governance ; 2,5 for highest)
(TI2) Installed capacity RE / total energy demand	(EI2) Interest rate	(SI2) Educational Level, at least Bachelor's or equivalent, population 25+, total (%) (cumulative)	(EVI2) Natural Disaster Risk Index	(GPI2) Corruption Perceptions Index (C (higher score is less corrupt)

(TI3) Nautical distances to Belgium (or land-distances in case of pipeline)	(EI3) Inflation, GDP Deflator	(SI3) Human Development Index (1 for best, 0 for worst)	(EVI3) Water Stress Index	(GPI3) Government Efficiency Index (-2,5 for least and 2,5 for most efficient)
(TI4) Hydrogen export potential (Potential for renewable energy – estimated domestic use)	(EI4) Corporate tax rate	(SI4) Healthcare score	(EVI4) Change in Forest Area (%):	(GPI4) Fragile States Index (FSI) (higher indicator score is more fragile)
	(EI5) Hydrogen strategy with export potential			
	(EI6) Organisation assigned to develop the hydrogen industry			
	(EI7) Are there local incentives for hydrogen production?			
	(EI8) Supportive framework for external investors			

Table WP6-1: Criteria for assessment tool for countries to score their attractiveness for H2 export to EU/BE

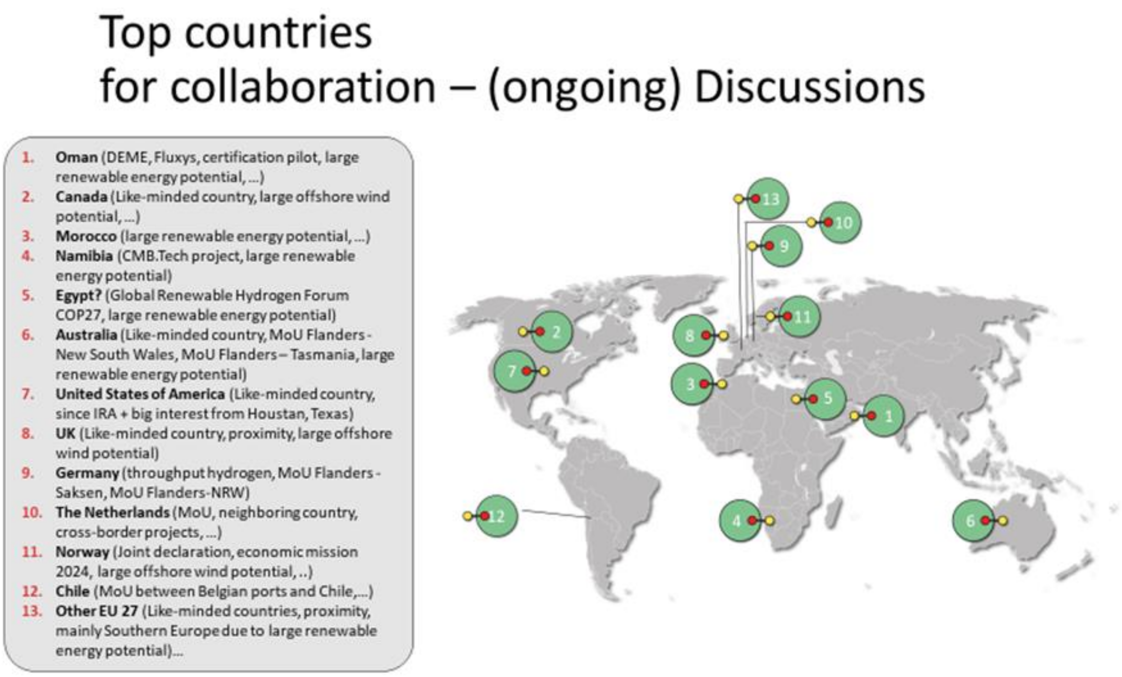


Figure WP6-5: 'gut-feel' classification of top countries to work with from BE companies' perspective at the end of 2023.(Source Belgian Hydrogen Council). Since that, Brasil & India have entered the list of 'interesting countries'...

Task 6.3

Activities

Analysis –roadmapping import & receiving EU infrastructure

In deliverable 6.3, WaterstofNet has summarised the different import strategies of Belgium and the neighbouring countries and described the status and plans of the Hydrogen (& derivative) transport and storage infrastructure in Belgium and the neighbouring countries. A number of legislative bottlenecks to be tackled are added.

An example of the status of the H2 pipeline network in our region, based on the most recent announcements and modifications, is given in Fig. WP6-6.

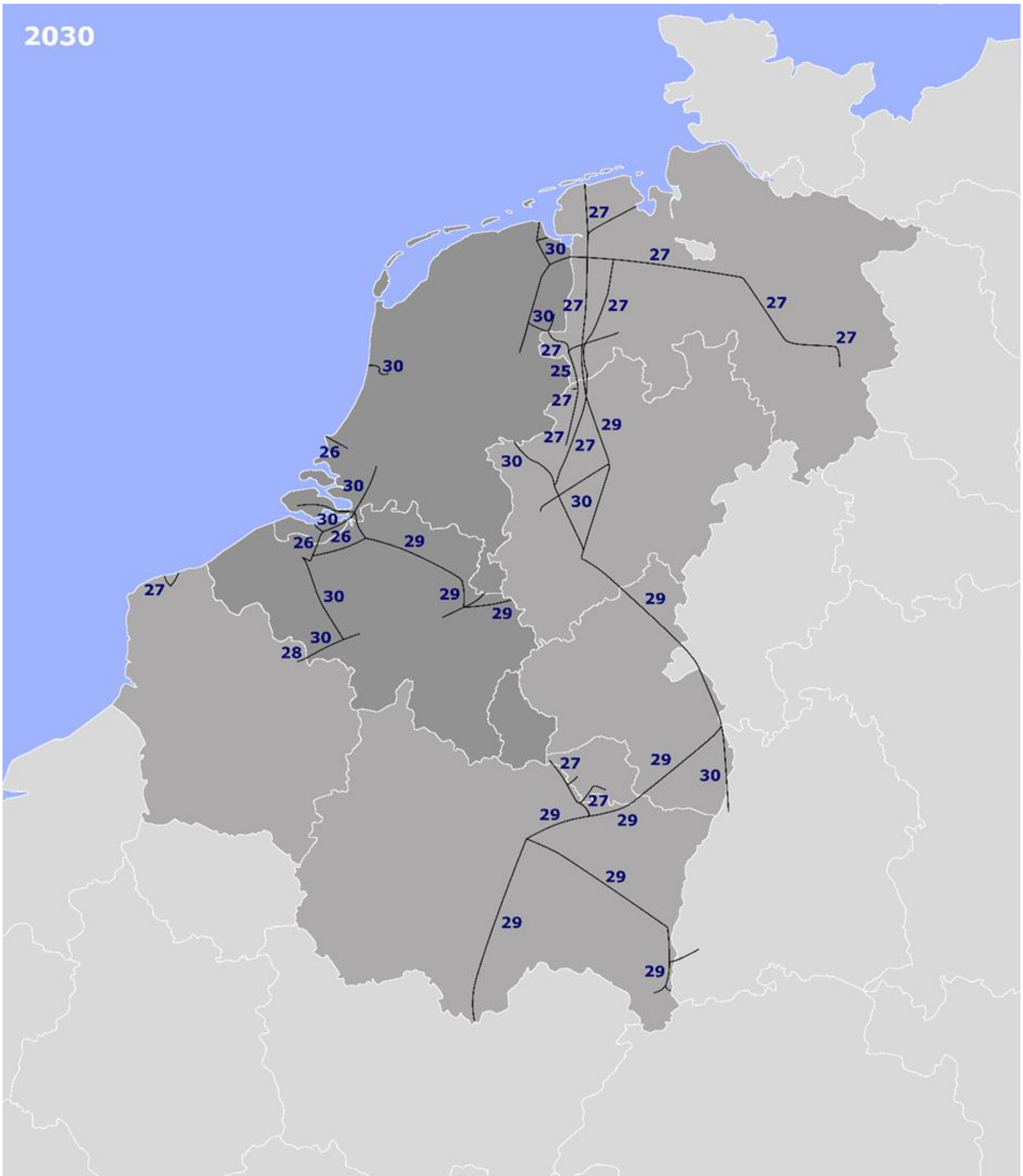


Fig WP6-6: Status of the hydrogen backbone development in 2030, based on public announcements

Techno-economic analysis KULeuven:

The analysis conducted by KU Leuven for the EU shows a gradual phase-out of SMR-based hydrogen production in favour of imports and electrolytic hydrogen. Between 2023 and 2040, 70 Mt of hydrogen is produced via SMR, while 170 Mt is produced through power-to-hydrogen (P-t-H) technologies. Investments in SMR-CCS contribute only 12.4 Mt in the reference scenario, while 180 Mt is imported. The results highlight that hydrogen supply strategies depend on the cost structure of production technologies: an optimal mix of high-CAPEX, low-OPEX and low-CAPEX, high-OPEX P-t-H technologies emerges. Sensitivity analyses indicate that lower natural gas prices increase the role of SMR-CCS, while expensive hydrogen imports reduce reliance on imports and shift production towards P-t-H and SMR-CCS. Moreover, constraints on renewable electricity expansion delay P-t-H uptake, increasing reliance on imports and, to a lesser extent, SMR-CCS.

These insights are particularly relevant for Belgium, where the hydrogen supply composition is expected to mirror the European trends. Given Belgium's limited renewable potential and its strategic position as a key industrial hub, a similar balance between domestic hydrogen production and imports is likely. Our findings provide a valuable reference for Belgian policymakers in designing hydrogen strategies that align with economic and climate objectives while considering the constraints of the local energy system. [1]

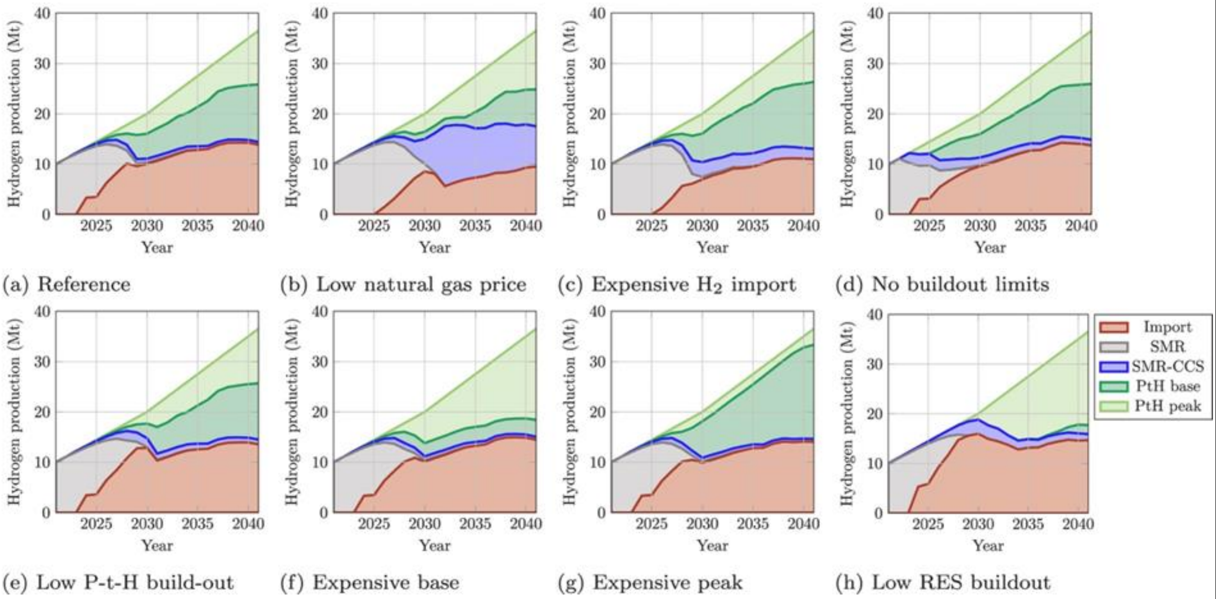


Figure WP6-6 Annual hydrogen production for the EU in the reference case (a) and in the sensitivities (b-h) [1]

[1] Hoogsteyn, A., Meus, J., Bruninx, K., & Delarue, E. (2025). Interactions and distortions of different support policies for green hydrogen. *Energy Economics*, *141*, 108042.

Publications

- Hoogsteyn, A., Bruninx, K., & Delarue, E. Carbon Contracts for Difference Design: Implications for Energy Markets and Carbon Pricing Mechanisms. *Available at SSRN 4661138*.
- Hoogsteyn, A., Meus, J., Bruninx, K., & Delarue, E. (2025). Interactions and distortions of different support policies for green hydrogen. *Energy Economics*, *141*, 108042.
- Bruninx, K., Moncada, J. A., & Ovaere, M. (2022). Electrolytic hydrogen has to show its true colors. *Joule*, *6*(11), 2437-2440.
- Derez, M., Hoogsteyn, A., & Delarue, E. Optimisation of Electrolyser Operation: Integrating External Heat in Proton Exchange Membrane and Solid Oxide Electrolysers. *Available at SSRN 4783257*.

Presentations

- Hoogsteyn, A., Meus, J., Bruninx, K., & Delarue, E. (2024, March). Support mechanisms for hydrogen: Interactions and distortions of different instruments. In *EPHyC European PhD Hydrogen Conference, Location: Ghent, Belgium*.
- Hoogsteyn, A., Bruninx, K., Meus, J., & Delarue, E. (2023, February). Support mechanisms for accelerating decarbonization using hydrogen. In *Pathways to a Clean, Stable, and Sustainable Energy Future, 44th IAEE International Conference, February 4-9, 2023*. International Association for Energy Economics.

- Hoogsteyn, A., Derez, M., Meus, J., Bruninx, K., & Delarue, E. (2024, June). Technological representation of Power to Hydrogen in long-term planning models. In *International Energy Workshop, Location: Bonn, Germany*.

WP7 Market analysis, valorization potential and enabling conditions (Tomas Wyns)

This Workpackage focusses on converging climate friendly technologies to assess the impact on full process integration (example of full circular value chains) and the impact of the use of climate friendly technologies on value chains with a consumer focus. The workpackage finally looks at the policy impacts of the PROCURA project and the valorisation potential.

WP 7.1: Process integration / Identify synergies and symbiosis between energy sector and chemicals/steel production

In this task a new climate friendly technologies database (for industrial technologies) was developed. The database was used to define a new value chain model that focuses on the residence time of carbon in circular materials. The latter is extremely relevant given new carbon accounting initiatives by the European Commission that seek to assess the potential use of carbon capture and utilisation.

Climate Friendly Technologies database

The "INDUSTRIAL CLIMATE FRIENDLY TECHNOLOGY DATABASE (V6)" assessed **98 industrial technologies**. The database focuses on technologies across four sectors: **Chemicals production, Refining, Hydrogen production, and Steel production**.

The types of technologies assessed include:

- Electrification
- Use of Hydrogen
- CCUS (Carbon Capture, Utilization, and Storage)
- Alternative feedstocks
- Process intensification
- Biobased
- Chemical recycling
- CC (Carbon Capture)
- Incumbent technologies (used as benchmark)

The database contains assessed data (where available) for each technology, including:

- Type of technology and incumbent process
- New process description
- Sector
- Input and outputs
- Specific energy use
- Specific CO2 emissions
- TRL (Technology Readiness Level)
- OPEX (Operating Expenditure)
- CAPEX (Capital Expenditure)
- Sources and references

The database provides details on various processes and technologies within these categories, such as Oxidative Dehydrogenation of Ethane (ODE), Chemical Looping (CL)-ODE, Methane-to-syngas-to-DME-to-olefins, Bio-fermentation of methane to methanol, Photo-catalytic Water Splitting, Photo-electrolysis, and many others aimed at reducing energy use and CO2 emissions in industrial processes.

The database has been benchmarked to other industrial technology databases such as the IEA clean energy technologies guide and is at this time probably one of the most comprehensive climate friendly technology overviews for the chemical industry.

Carbon management model

A new polymer oriented model was developed with the goal to assess key technologies featured under the Procura project (incl. use CCU and use of hydrogen) within the context of system integration and over the full value chain and multiple circular life-cycles. The main goals of this model are:

- Estimating the loss of carbon (to the atmosphere) over the full value chain (incl. recycling) of basic polymers production (a major industry in Belgium)
- The impact on energy use of combined innovative process technologies
- Estimation of hydrogen demand in a new (to be established industry) of circular plastics (e.g. via CCU)

This model is a first of a kind because, as opposed to most model that assess lifecycles, it runs over multiple lifecycles until the depletion of the original carbon input to the process. This is done to assess the longevity of carbon stored in materials. The latter is important to valorise climate benefit of carbon capture and utilisation (in particular, if the carbon originates from fossil sources). Ideally, the carbon remains locked for a period of around 100 years (comparable to the lifetime of CO2 in the atmosphere). The model has been applied to major high value chemicals (HVCs) and polymer streams (e.g. PET, PE, …), representative of the production in Belgium. When applying breakthrough process innovations in the model for production of HVCs as well as the most advanced processes for plastics recycling and CCU, the results show still a critical loss of carbon to the atmosphere over a time period much shorter than the residence time of CO2 in the atmosphere. This result has direct policy implications such as the need to extend the useful lifetime of materials and avoid downgrading of plastics.

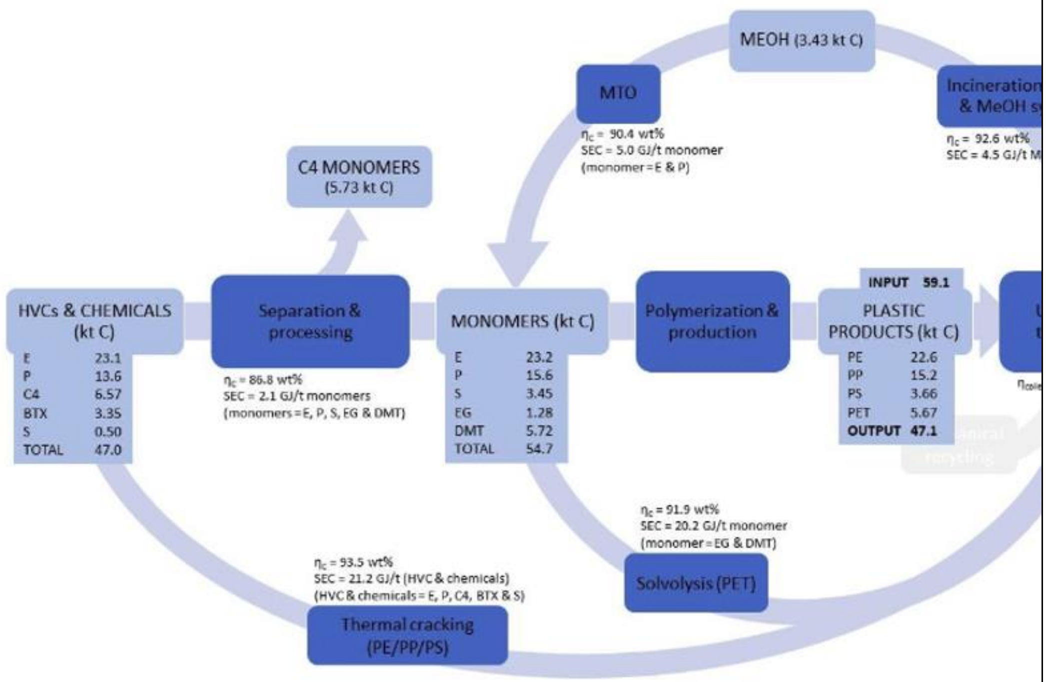


Figure: Block diagram of the first chemical recycling loop of plastic packaging in the ELEC route, starting from 59.1 kt C. A solvolysis process is applied for PET waste and a thermochemical recycling process for PE, PP and PS. Rest streams of the chemical recycling processes are treated in a combined unit of oxy-combustion with CCU and methanol synthesis to obtain new monomers via MTO

The carbon management report has been finalised. This report has been reworked into a journal article that has been published in a high impact journal. The new methodology has also been presented to DG Clima in support of the development of the EU's carbon management approach. It has also been shared with EU industrial stakeholders that have an interest in CCU(S).

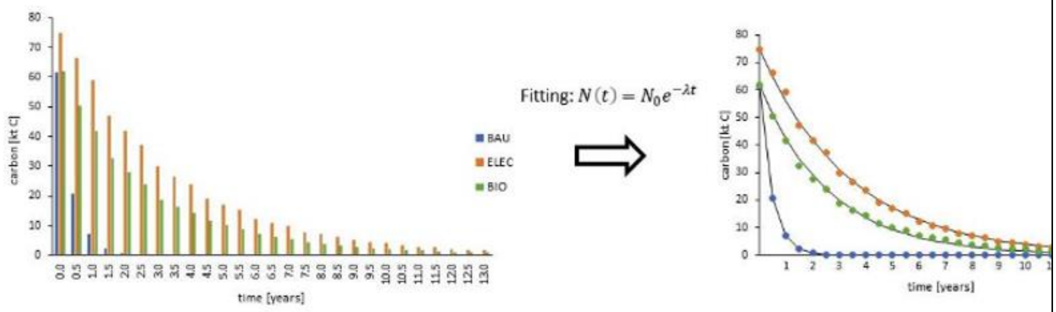


Figure : The amount of carbon as function of time; (left) bar graph of the embedded carbon in packaging plastics in the three different routes and (right) fitting of an exponential decay function through these bars.

One of the groundbreaking and policy relevant results of this research is the development of a (relatively) simple assessment formula for the calculation of the longevity of carbon in materials (with multiple recycling loops). This formula introduces the new concept of a half-lime time of carbon in materials (via a negative exponential function). Otherwise said, the condensed formula translates circular material flows into a time estimate showing the gradual leakage of carbon from materials loops to the atmosphere. The fact that complex physical, chemical recycling and CCUS routes can be distilled into a simple outcome has high policy relevance.

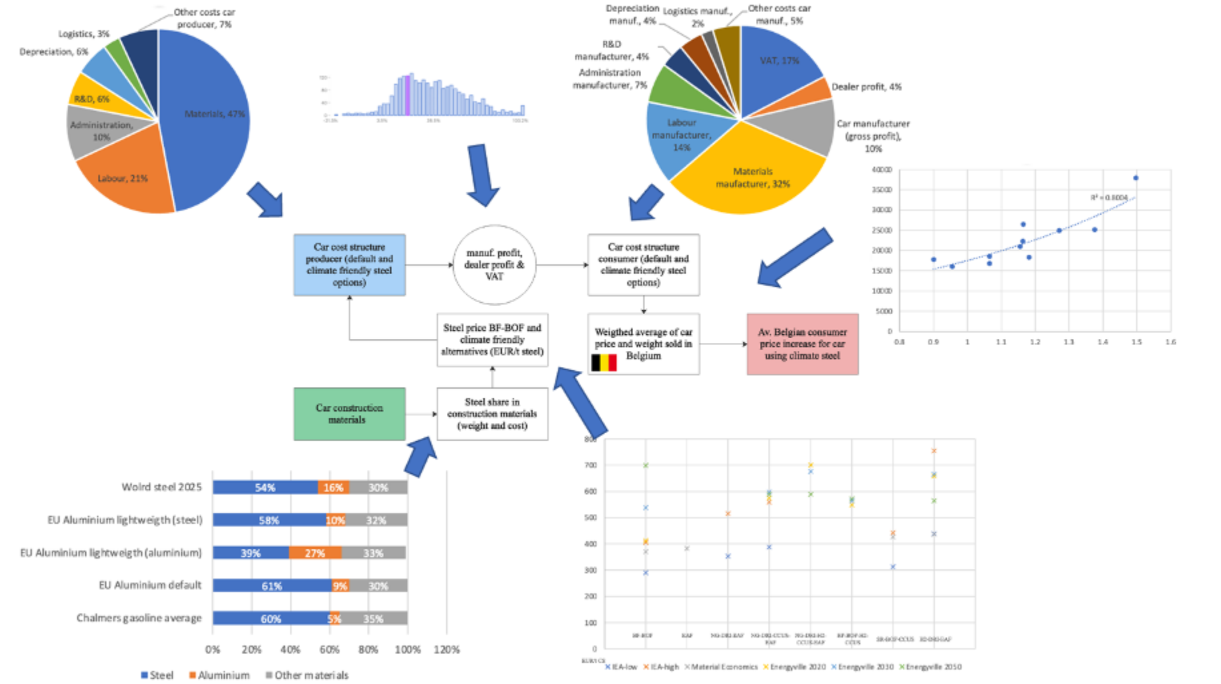
To further expand and test the use of this model it has been applied to major carbon capture and utilisation processes and applications. The goal was to determine the longevity of (captured) carbon in the production and use of new products and materials. The examples used were the packaging, e-fuels, textiles and construction value chains.

WP 7.2 Value Chain analysis / Identify (economic and other) opportunities and valorization in technological shift to H2, CCU and circular carbon from a value chain perspective

In this task the impact of the use of climate friendly technologies for steel and polymers throughout two key value chains is assessed with the focus on consumer impact and policy responses. This research is relevant because it measures the impact of measures such as the introduction of clean material standards.

Value chain analysis: Consumer impact of the application of climate friendly materials and technologies

Based on new insights and research the material value chain models for steel and (packaging) polymers were re-buildwith the goal to obtain results with higher granularity and reliability. Value chain analysis for automotive, packaging and food was completed with material flows for respectively steel, PET and fertilisers.



The car materials and production cost model developed for the Procura project

The main goal of the value chain analysis is to model how addtional costs (capex and opex) for climate friendly production of steel, plastics and fertilisers is passed through the whole value chain and how consumer prices (incl. taxes) would be affected. In this approach a full pass-through of (addtional) costs is assumed (incl. actors along the value chain keeping same profit margins).

Value chain impacts

The results of the model show a limited impact on consumer prices (+0.8% to 4%) for car produced using green steel, +2 to 5% for premium soft drink (1.5l) and +5 to 15% for low-cost soft drink (1.5l). These results are however higher compared to previous estimates and literature, which did not use a detailed integrated model as applied here. It is likely that the impact is even higher in countries with lower purchasing power parity.

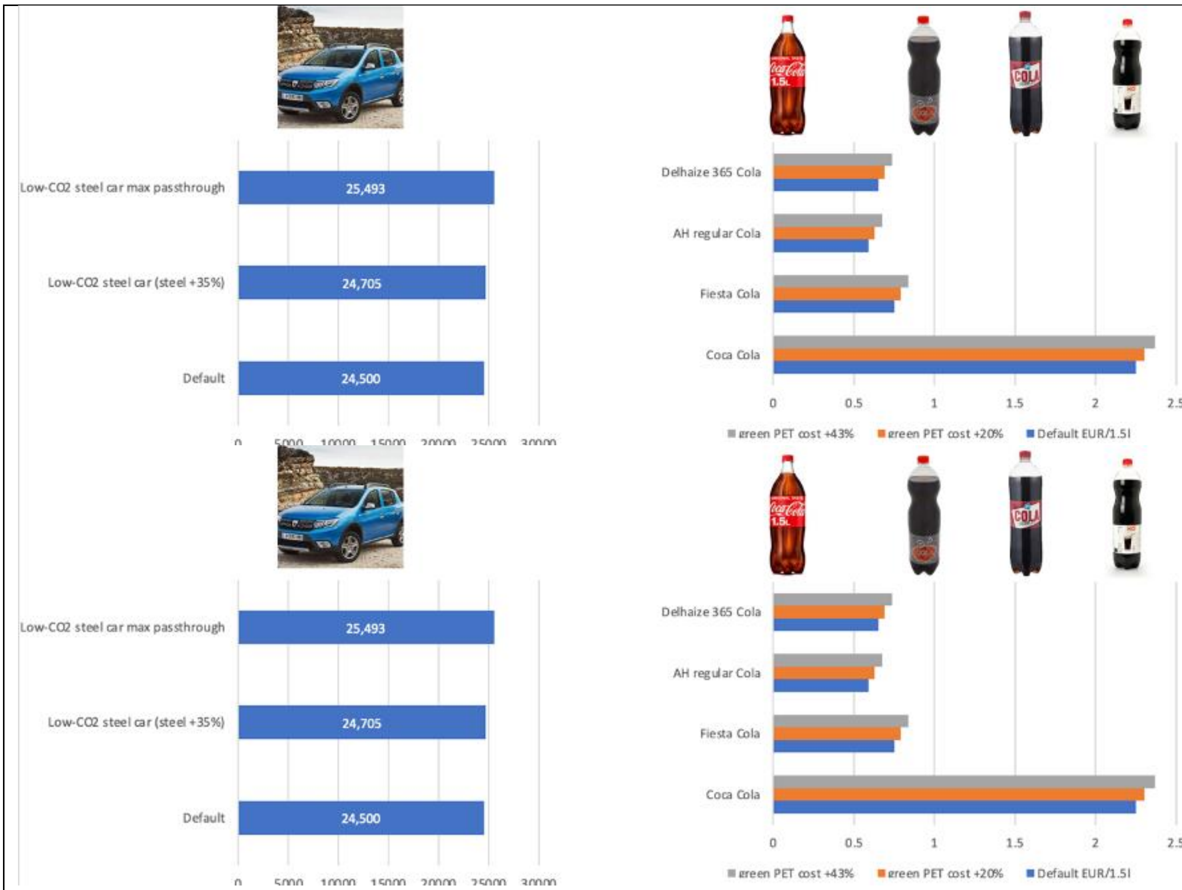


Figure: Cost impact of green steel use in cars (left) and climate friendly polymers in soft drinks

A paper has been developed that introduces the above mentioned methodology and applies to the green steel and green polymers value chains. It is currently in the process of being prepared for submission to a scientific journal.

Policy relevance and recommendations

This research looked specifically at demand side policies that can enable a lead market for green steel, plastics and fertilisers. While supply side policies (such as the EU Emissions Trading System) might induce producers to deploy clean technologies, there remains the risk of competitive distortion and market loss.

From the demand side, this research shows that if producers of green steel, plastics etc. can pass through the full cost of green production and keep existing profit margins, the price of final products increases only slightly. If consumers need to be shielded from these (small) price increases, fiscal instruments could be used. For instance, lowering the VAT for cars built using green steel from 21% to 19% would cover the production cost increase. Such instrument would give steel producers and car manufacturers an incentive (and market) to produce and use green materials.

The policy relevance of this work has dramatically increased since the European Commission's presentation of the clean industrial deal (feb. 2025) which considers the introduction of labels and standards for clean materials (e.g. steel).

WP 7.3 Policy impact and valorisation / Identifiy the enabling conditions for industrial transition towards H2, CCU, circular carbon

Two policy papers are developed relating to the final results of the PROCURA project:

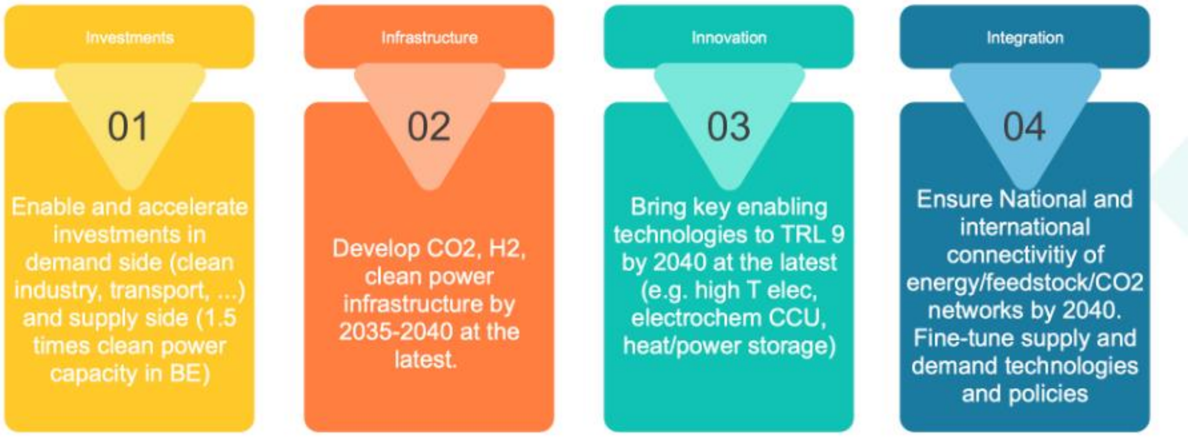
- A policy paper discussing the impact and implications for public policy following the development of the PROCURA roadmap using the updated TIMES-BE model. Publication 30.04.2025
- A Valorisation insights paper discussing the valorisation options and pathways for the technological, modelling and other research results from the PROCURA project. Publication 30.04.2025

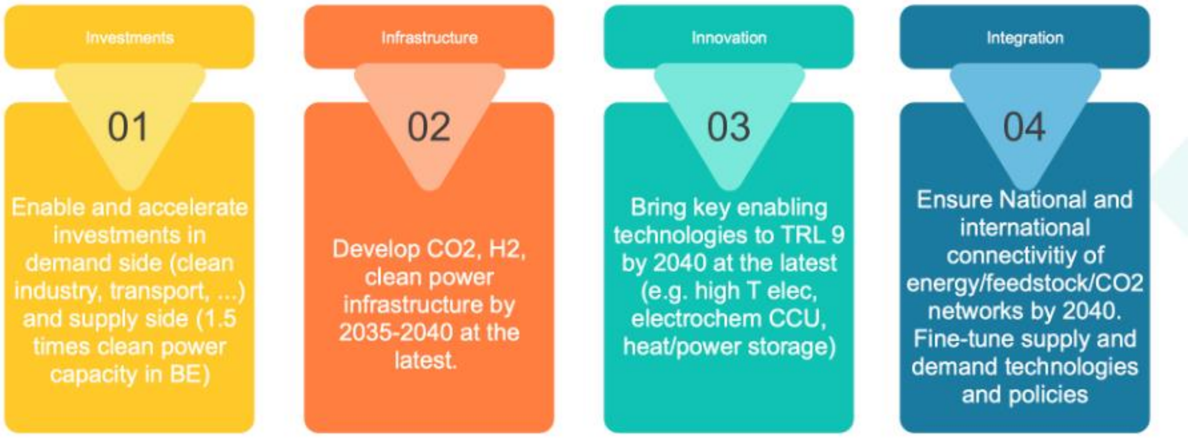
Procura Roadmap Policy Insights: "4i-s: Investment, Innovation, Infrastructure and Integration. Challenges and Opportunities to implement the PROCURA CCUS/H2 roadmap."

Implementing the CCUS and H_2 roadmap in Belgium faces significant policy challenges, notably in the area of investment. Over the next 15-20 years, massive financial commitments are required on both the demand and supply sides, with estimates indicating a need for investments equivalent to 1.5 times Belgium's current power generation capacity. This capital influx must support the establishment of robust facilities and technologies that will drive the transformation of Belgium's energy demand and supply landscape.

Moreover, infrastructure development is critical; substantial projects are needed for CO_2, hydrogen, biomass, electricity, and circularity, with the ambitious goal of having these systems fully operational within the next 10-15 years (by 2035-2040) as to enable the full implementation of climate friendly technologies in all economic sectors by 2050 at the latest.

In parallel, innovation plays a pivotal role in overcoming integration challenges within the roadmap. Cutting-edge solutions are required to drive advancements such as new electrification methods for heat, cost-efficient CO_2 capture technologies, and power-to-chemicals processes.





Additionally, there is a pressing need to ensure seamless integration across the entire value chain—from demand and supply to storage. This integration is not limited to Belgium alone but extends to a broader network of regional cooperation, encompassing areas like Flanders, Wallonia, Germany, the Netherlands, France, and beyond. The coordinated efforts across these diverse regions will be essential to realize a fully integrated and competitive ecosystem that supports Belgium's transition to a low-carbon future.

Procura Valorisation insights: "What's next for CCUS/H2 R&D, deployment and supporting research."

Abstract: The PROCURA project has delivered groundbreaking, multi-dimensional insights across its seven work packages, fundamentally strengthening Belgium's pathway toward a low-carbon future.

The upgraded TIMES-BE model now stands as one of the most advanced equilibrium tools available in Belgium —integrating both supply and demand dynamics while enabling detailed scenario analysis.

For instance, within WP1, the project has developed and validated correlations for various carbon capture (CC) technologies using a dynamic Decision Support Tool (DST). Which will enable companies to easier determine investment options into carbon capture technologies.

Meanwhile, WP2 and WP3 deliver critical techno-economic assessments for Power-to-X processes and CCU applications, framing long-term scenariost hat account not only for technology performance but also for shifts in TRL levels across emerging and mature technologies. Again this will enable the public and private sectors to make better informed policy and investment decisions.

In WP4, the innovative PV-integrated electrolyser system demonstrates a promising pathway for solar fuel technologies—where emerging solutions, although currently at lower TRL levels (around TRL 3–4), can be matured into scalable, integrated systems.

Furthermore, WP6 expands the valorisation perspective by mapping international hydrogen value chains and identifying cross-border collaboration opportunities. With Belgium's central location in the EU and the presence of major sea-harbours and clusters, Belgium can become a major hub in future hydrogen derivatives and CO2 market.

The demonstrator developed under WP5 integrates the cutting-edge electrochemical CCU technologies and provides a real-world testbed for performance validation under operational conditions. By demonstrating the feasibility of combining carbon capture, renewable integration, and Power-to-X pathways in a pilot environment, advanced the related technologies to higher readiness levels (towards TRL 7). This not only validates the underlying concepts but also provides essential feedback for further optimization, ensuring that the innovations can be rapidly and effectively translated into industrial processes.

WP7 unlocks the full market potential of PROCURA's innovations by linking technology developments to tangible economic and environmental benefits. It introduces the comprehensive Industrial Climate Friendly Technology Database, cataloguing 98 technologies across chemicals, refining, hydrogen, and steel—including detailed metrics like TRL, energy use, and emissions—to benchmark both mature and emerging processes. Complementing this, a novel carbon management model assesses the longevity of carbon storage in materials across multiple recycling loops, offering groundbreaking policy insights through a "half-life" concept. Additionally, WP7's value chain analysis quantifies the modest consumer price impact of shifting to green production, paving the way for strategic public–private partnerships and informed policy adjustments.

By combining these outputs, the PROCURA project positions Belgium not only as a regional hub for technological innovation but also as an attractive ground for public–private partnerships aimed at accelerating technology readiness, industrial deployment, and market integration in the energy transition.

6. INNOVEREND KARAKTER VAN DE BEREIKTE RESULTATEN / INNOVATIVE CHARACTER OF THE RESULTS ACHIEVED

Onderbouwing met verwijzing naar wetenschappelijke publicaties.
Supported with reference to scientific publications

WP1:

- The shortcut correlation of the MEA absorption process (31 – 1250 kt/y) was submitted and is currently in the *third round* of the review process. A preprint of the article is available on SSRN:
    - Kim, S.M. and Léonard, G., CO_2 Capture Technologies and Shortcut Cost Correlations for Different Inlet CO_2 Concentrations and Flow Rates. 1. Chemical Absorption. Available at SSRN: https://ssrn.com/abstract=4967576 or http://dx.doi.org/10.2139/ssrn.4967576
- A paper on small-scaled MEA and PolyActive membrane processes was submitted and accepted to the ESCAPE35 (European Symposium on Computer-Aided Process Engineering) conference (July 2025):
    - Kim, S.M. and Léonard, G., 2025. Short-cut Correlations for CO_2 Capture Technologies in Small-Scale Applications. ESCAPE 35 – European Symposium on Computer Aided Process Engineering.
- A journal article draft of the shortcut correlations of Selexol, PolyActive, and Polaris membranes was written and is currently going through an internal review. After this review, the article will be submitted to a publisher for further peer reviews for publication.
- To wrap up the results of WP1, a third journal article is planned where the Belgian case studies using shortcut correlations, and the DST will be presented. The anonymized industrial case studies as well as Belgian industrial profiles will be used to identify suitable CC options at various industrial scenarios.

WP2:

- State of the art techno-economic models were developed for both methanol production, ammonia generation and cracking, as well as syngas generation. Furthermore, a life cycle analysis was conducted for the former two cases. These have given rise to many presentations for specific audiences within and outside the boundaries of the PROCURA project, including interactions with the H_2 import coalition which is also very active around the topic. The work has also supported the validation of assumptions used in WP3. The analysis of ongoing projects and the policy landscape has also given the researchers a broader understanding of the topic, which is critical to continue research in this area. No specific academic publication has been derived from this work, although elements of the work may find their place in a future publication.

WP3:

- The TIMES-BE energy system model of VITO/Energyville has undergone a metamorphosis since the start of the PROCURA project. Every sector has been upgraded in the model in terms of detail, updated academic and industrial data points based on literature research, modeling results from other work packages, company interviews and direct feedback on specific technologies, sector coupling, scenario development, policy reviews and benchmarking with other (ETSAP TIMES) energy models nationally and internationally. The result is a unique energy system investment model for Belgium which has become the benchmark.
- One of the results is the creation of the PATHS2050 "The Power of perspective" website, where model results and discussions have made publicly available, consisting out of various scenarios and specific sensitivities. They have been built based on PROCURA research questions and elaborated by input from other stakeholders such as Febeliec, political parties and national and regional governments. The current version of the website (late 2022 and beginning 2023) will be updated and presented in a public event on 23th April 2025. Website: . Future development is taking place in follow-up ETF projects such as ETF CIREC, ETF HEFAISTOS, ETF TRILATE, ETF GALILEO and ETF CEEP-IT.

WP4:

- KU Leuven developed a structured and comparative framework to assess a wide range of solar fuel technologies. This included a combination of technology mapping, TRL analysis, SWOT assessment, and detailed techno-economic evaluation. A notable innovation was the integration of real-world case studies — such as Synhelion (solar thermochemical), Photanol (photobiological) and Fusion Fuel (integrated PV-electrolysis) — allowing the analysis to go beyond theory and reflect current industry developments.

- While no scientific publication resulted from the exploratory work done in Tasks 4.1-4.4, the work did enable the integration of solar fuel pathways into broader energy system models (TIMES-BE) by compiling a functional parameter set for the different solar fuel technologies (based on > 80 publications), supporting strategic planning and long-term technology forecasting. This holistic approach provided both depth and breadth, helping to position solar fuels within the wider energy transition landscape.

WP5:

WP6:

WP7:

- An innovative carbon management model has been developed that as a first of its kind uses mulitiplecircular materials routes to assess the residence time of carbon in materials. This resulted in a publication in a high impact journal. *Stijn Van der Perre, Oleksii Mynko, Kevin M. Van Geem, Tomas Wyns, Modelling of carbon flows in the value chain of packaging plastics in the context of sustainable carbon management, Sustainable Production and Consumption, Volume 49, 2024, Pages 12-27, ISSN 2352-5509, https://doi.org/10.1016/j.spc.2024.06.002*.
- New cost-passthrough models have been developed for steel in cars and polymers in packaging. A scientific paper describing the model, presenting its results and policy implications is being prepared for submission to journal. *Wyns, T., Khandekar, G., 2025, Clean steel and polymers value chains: consumer impact and policy responses.*
- A state of the art, industrial clean technology database has been developed, which for chemical process technologies outperforms major global technology databases such as the IEA clean energy technology guide. *Wyns, .T, Van der Perre, S., 2023, Clean industrial technology database (V6)*

7. HET ECONOMISCH EN HET SOCIALE EFFECT IN BELGIE / THE ECONOMIC AND SOCIAL IMPACT IN BELGIUM

De begunstigde licht toe in welke mate het project heeft aanleiding gegeven tot een belangrijke diversificatie van energiebronnen of tot verhoging van competitiviteit op de energiemarkt, de instandhouding en / of bevordering van de tewerkstelling, de beperking van de nettarieven, heffingen en / of energiekost voor de consument
The beneficiary explains to what extent the project has led to a significant diversification of energy sources or to an increase in competitiveness on the energy market, the maintenance and/or promotion of employment, the limitation of network rates, levies and/or energy costs for the consumer.

The results of the PROCURA project can, through the insights generated, have a positive impact on the diversification of energy sources and on the adequacy of the energy system. Long-term investment models calculate the most cost-optimal path to a highly de-fossilized energy system, this can benefit the total cost of the system. On the one hand, these insights are improved to the highest possible technological level of detail, given the most recent evolutions in Belgium and Europe (buildings, potential of heat networks, import of molecules, ambitions with regard to greenhouse gas reduction, Hydrogen vs direct electrification, etc...) On the other hand, the social perspective in cost optimization is supplemented with the perspective of security of

supply (both from the point of view of electricity production and the high-voltage grid) and the market / consumer perspective.
In addition the blue hydrogen question and the further extension of the nuclear power plants are discussed in a techno-economical and social context.

8. HET EFFECT OP KLIMAAT EN MILIEU IN BELGIE / THE IMPACT ON CLIMATE AND ENVIRONMENT IN BELGIUM

De begunstigde licht toe in welke mate het project heeft aanleiding gegeven tot de beperking van het risico voor de volksgezondheid, beperking CO2 uitstoot, beperking risico op ongevallen.
The beneficiary explains to what extent the project has led to the reduction of the risk to public health, reduction of CO2 emissions, reduction of the risk of accidents.

The PROCURA project has no direct impact on the reduction of CO2 emissions or public health, but can indirectly make a very important contribution by creating a vision and answering some crucial long-term questions. By providing a Roadmap for PtX and CCU in Belgium the research and development for academia but also investments for industry will get clear border conditions and focus.
The PROCURA project combines the expertise of the various scientific institutes in Belgium and develops on one hand models that can support the energy transition with scenario projections and on the other hand also implements scientific ideas in concrete developments like the large scale prototype electrolysys demonstrator (WP5) or the lab demonstrator of a solarfuel device (WP4). This is of great importance for, among other things, investment decisions in public infrastructure in the context of the European Green Deal and the economic recovery.
Energy system analysis can map the interaction between green hydrogen and the energy system, which is important for public infrastructure investments. It is also important for industry that scenario exercises and long-term projections provide insight into the possible evolutions of the energy system as a background for its own investment decisions.
It is the objective that necessary investments will result from the energy market prediction model calculations, and a total cost to the energy system, which is important information for the regulator.

9. EVOLUTIE IN NIVEAU VAN TECHNOLOGISCHE MATURITEIT (NMT)/ EVOLUTION IN LEVEL OF TECHNOLOGICAL MATURITY (TRL)

Opgave van
• het NTM bereikt op het tijdstip van de vorige vergadering;
• het NTM dat geacht wordt te zijn bereikt op het tijdstip van de vergadering zelf in functie van de initieel gecommuniceerde vooruitzichten alsook
• het NTM dat daadwerkelijk werd bereikt.
Statement of
• reached the TRL (Technology Readiness Level) at the time of the previous meeting;
• the NTM that is deemed to have been reached at the time of the meeting itself based on the initially communicated prospects as well as
• the TRL that was actually achieved.

WP5: CO2 reduction demonstrator: TRL 6->TRL 7
WP4: Solar Fuel demonstrator:TRL 3-> TRL 4

10. FORMEEL ENGAGEMENT TOT VERSPREIDING OF PUBLICATIE VAN DE BEREIKTE RESULTATEN/FORMAL COMMITMENT TO DISTRIBUTION OR PUBLICATION OF THE RESULTS ACHIEVED

The dissemination of the results is realized in different ways.
- Scientific publicatons
- Website of PROCURA ()ttps://procurabelgium.be/en

An important dissemination path is the industrial advisory board meeting, planned in June 2022 with the member of the board and the project officers. The interest in the project is reflected by the number of industrial board members.

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11. EVENTUELE VALORISATIEVOORUITZICHTEN, REKENING HOUDEND MET DE RESULTATEN VAN HET PROJECT/ POSSIBLE VALORISATION PROSPECTS, TAKING INTO ACCOUNT THE RESULTS OF THE PROJECT

Bespreek, vertrekkende van de resultaten van het project, hoe de resultaten zouden kunnen gebruikt(gevaloriseerd) worden. Behandel daarbij zeker de volgende aspecten:

- *het verdere traject naar eventuele valorisatie (risico's, planning, kosten, ...);*
- *de vertaling van de resultaten naar concrete processen/producten/diensten;*
- *de marktkansen/vooruitzichten van deze resultaten;*
- *de concrete industrialisatie of toepassing van de resultaten (waar worden die uitgevoerd, zijn er daar nog specifieke risico's, etc.).*

Als er belangrijke afwijkingen in plus of in min zijn t.o.v. de vooruitzichten bij goedkeuring van het project, behandel dan expliciet de gevolgen daarvan.
Starting from the results of the project, discuss how the results could be used (valorized). Be sure to address the following aspects:

- the further path to possible valorization (risks, planning, costs, ...);
- the translation of the results into concrete processes/products/services;
- the market opportunities/prospects of these results;
- the concrete industrialization or application of the results (where are they carried out, are there any specific risks, etc.).

See WP7.3, p.35

12. TOELICHTINGEN OF BIJKOMENDE COMMENTAAR (facultatief)

Geef hier, indien u dit nuttig vindt, commentaren die u niet elders in het formulier kon opnemen.

Door ondertekening van dit document verklaart de begunstigde dat de in dit document verstrekte informatie alsook de informatie in de leverbaarheden volledig, juist en betrouwbaar is.
Naam: **Hoedanigheid[2]:**   **Handtekening**

[2] Als bijlage dient een bewijs gevoegd waaruit blijkt dat de ondergetekende bevoegd is om de betreffende begunstigde entiteit wettelijk te verbinden.