Projet DRIVER du Fonds de Transition Energétique octroyé dans le cadre de l'appel de Novembre 2020

Délivrable 4 (D4) : Rapport sur l'impact du marché CO2 sur tout le système énergétique belge

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Note : En accord avec les représentants du SPF Economie, il a été convenu lors de la réunion de lancement du projet DRIVER, qui a eu lieu le 25 octobre 2021, que les livrables du projet peuvent être rédigés en français ou en anglais, moyennant un résumé en français. Le présent document est rédigé en anglais, langue dans laquelle ces résultats ont été publiés.

Résumé

En 2020, la Belgique a émis 82,7 MtCO_2, dont 23 MtCO_2 provenant des secteurs industriels. Le Captage et Utilisation du Carbone (CCU) et le Stockage du Carbone (CCS) sont des stratégies clés pour la décarbonation de ces industries. Dans le cadre du CCU, le CO_2 peut être valorisé en tant que matière première pour la production d'hydrocarbures de synthèse, ajoutant ainsi de la valeur au CO_2. Cependant, tout comme le CCS, le CCU requiert une énergie supplémentaire. Compte tenu des importantes émissions de CO_2 disponibles, ces besoins énergétiques pourraient être élevés, influençant le système énergétique belge et les coûts totaux de la transition. En plus de valoriser localement le CO_2 en le convertissant en hydrocarbures de synthèse, la Belgique envisage d'importer des hydrocarbures de synthèse depuis des régions riches en énergies renouvelables, conformément à la Stratégie fédérale belge sur l'hydrogène. Cependant, leurs coûts et les secteurs de déploiement restent très incertains.

Ce livrable se concentre sur deux piliers. Premièrement, il examine l'impact de la valorisation du CO_2 via le CCU sur le système énergétique belge. Plus précisément, il évalue la quantité de CO_2 pouvant être convertie en e-méthane, les modifications nécessaires dans la configuration du système

énergétique belge, et le volume de combustibles renouvelables qui devra encore être importé. Deuxièmement, il évalue les moteurs de la demande pour ces électro-fuels au sein du système énergétique belge. Compte tenu des incertitudes importantes concernant les coûts et la disponibilité des électro-fuels, cette analyse prend en compte les incertitudes associées aux coûts d'investissement, à la disponibilité des ressources et aux besoins énergétiques pour le système énergétique belge de 2020 à 2050. Finalement, une première étude sur le rôle de la taxe carbone dans le système énergétique belge est présentée.

Pour valoriser le CO_2 capté, deux scénarios sont envisagés : l'un où tout le CO_2 capté est utilisé pour la méthanation, et l'autre où seul le CO_2 nécessaire pour réagir avec l'hydrogène disponible est utilisé, le surplus étant stocké de manière permanente sous terre. Comme cas d'étude, cela a été appliqué au cluster industriel du port d'Anvers. Le scénario de pleine utilisation implique des coûts supplémentaires de 4,9 à 8,4 milliards d'euros par an, soit une augmentation de 11% à 19% par rapport à un scénario sans CCU. Cette dépense représente environ 1,2% du PIB belge de 2022. Le scénario produit 21,8 à 32 TWh de gaz naturel synthétique (GNS) et 17,1 à 25,3 TWh d'énergie thermique, nécessitant jusqu'à 11 TWh d'importations d'hydrogène, ce qui se traduit par une consommation d'électricité de 48,8 à 80,3 TWh et une demande de chaleur de 4,9 à 7 TWh. Cela nécessiterait, en Belgique, 59,2 GW de capacité photovoltaïque (PV) et 10 GW d'électrolyseurs—un objectif ambitieux, étant donné la capacité actuelle des électrolyseurs en Europe de 160 MW. En revanche, le scénario d'utilisation partielle produit 5,18 à 9,1 TWh de GNS en utilisant 8 à 14 TWh d'hydrogène importé et 0,47 à 0,83 TWh produit localement, selon les niveaux de demande d'hydrogène. Ce scénario utilise 16,3% à 41,6% du CO_2 capté, entraînant une réduction des besoins en électricité, des capacités d'installation PV plus réalisables et moins de gaz naturel importé par rapport au cas de référence. Ainsi, l'utilisation partielle du CO_2 associée au stockage semble plus pratique.

En plus de la production locale, la Belgique devrait importer des électro-fuels à base de carbone dans un avenir proche. Une solution potentielle "miracle" serait l'importation précoce de fuels renouvelables, supposés être neutres en carbone et largement disponibles. L'incertitude importante autour du coût de ces importations en fait le facteur le plus influent sur le coût total de la transition, avec une variabilité d'environ 45%. L'analyse de quantification des incertitudes identifie également les principaux moteurs pour l'importation des électro-fuels renouvelables d'ici 2050. Au-delà des coûts d'achat—où des coûts plus bas entraînent des importations plus élevées—elle indique que la disponibilité des petits réacteurs modulaires (SMR) nucléaires impacte principalement les importations d'e-ammoniac en remplaçant les centrales électriques au gaz à cycle combiné à l'ammoniac, le plus grand consommateur d'e-ammoniac. Cela réduit à son tour les importations d'e-méthane en diminuant la demande pour les cogénérations au gaz et les chaudières. Les importations d'e-hydrogène et d'e-méthanol sont influencées par la concurrence des technologies de transport alternatives et la demande industrielle, respectivement. En conclusion, le besoin en électro-fuels pendant la transition suggère que l'investissement continu dans les infrastructures de transport est judicieux. Par exemple, Fluxys, le gestionnaire du réseau de gaz belge, s'est déjà engagé à investir environ 1,3 milliard d'euros d'ici 2032 pour soutenir cette transition. Investir dans les infrastructures pour les électro-fuels pourrait également aider à atténuer les risques associés à l'indisponibilité potentielle des technologies miracles comme les SMR nucléaires d'ici le milieu du siècle.

Finalement, une étude préliminaire (Appendix A) illustre que l'impact d'une taxe carbone réduit significativement les émissions, mais n'atteint pas le même niveau d'efficacité exergétique que les systèmes de taxation basés sur l'exergie. Selon les critères de l'étude pour un système de taxation durable—générer des revenus suffisants (10 milliards d'euros), améliorer l'efficacité exergétique et maintenir de faibles émissions—une taxe carbone seule reste insuffisante. Par conséquent, il devient nécessaire de l'intégrer à un autre système de taxation pour maintenir les niveaux de revenus cibles. Ce travail servira de base pour les recherches futures.

Contents

1 Introduction

1.1 Overview

In 2020, Belgium emitted 82.7 $MtCO_2$, with 23 $MtCO_2$ originating from industrial sectors. Carbon Capture Utilization (CCU) and Carbon Capture Storage (CCS) are critical strategies for decarbonizing these industries. In the context of CCU, CO_2 can be valorized by using it as a feedstock to produce e-methane, creating value from CO_2. However, like CCS, CCU requires additional energy. Given the substantial CO_2 emissions available, these energy needs could be significant, altering the Belgian energy system and affecting total transition costs. In addition to locally valorizing CO_2 by converting it into e-methane, Belgium will supplement this resource by importing e-methane and derivatives (e.g., hydrogen, ammonia, methanol) from renewable-rich regions, as identified in the Belgian federal Hydrogen Strategy. However, their costs and deployment sectors remain highly uncertain.

First, this deliverable examines the impact of CO_2 valorization through CCU on the Belgian energy system. Specifically, it assesses how much CO_2 can be converted into e-methane, the necessary changes in the Belgian energy system layout, and the volume of renewable fuels that will still need to be imported. Second, it evaluates the drivers of demand for these electrofuels within the Belgian energy system. Given the significant uncertainties surrounding the costs and availability of electrofuels, this analysis considers the uncertainties associated with investment costs, resource availability, and energy demands for the Belgian energy system from 2030 to 2050. Finally, a first study on the role of carbon tax on the Belgian energy system is provided.

The report is structured as follows: first, we describe the Belgian energy system model adopted for this analysis (Subsection 2.1). We utilize a whole-energy system optimization model that considers power, heating, mobility, and non-energy demand, tailored to the Belgian context. This model integrates a snapshot formulation, optimizing the energy system layout from a greenfield perspective, and a pathway formulation that optimizes investments at each stage of the transition. These models include a CCS and CCU layer to quantify energy requirements and analyze how the layout and costs of the Belgian energy system evolve when industrial CO_2 is either stored, used as feedstock for e-methane, or both. We then present the results on the impact of using CCS and CCU in the Belgian energy system (Subsection 3.1). Then, we illustrate the main drivers for the need for electrofuels in the Belgian energy system (Subsection 3.2). Finally, we illustrate the role of a carbon tax in reducing GWP emissions and improving efficiency.

1.2 Main scientific outcomes related to this deliverable

- Coppitters, D., Tsirikoglou, P., De Paepe, W., Kyprianidis, K., Kalfas, A., and Contino, F. (2022). RHEIA: Robust design optimization of renewable hydrogen and derived energy carrier systems. *Journal of Open Source Software*, 7(75), p. 4370.

- Coppitters, D., Costa, A., Chauvy, R., Dubois, L., De Paepe, W., Thomas, D., De Weireld, G., and Contino, F. Energy, Exergy, Economic, and Environmental (4E) analysis of integrated direct air capture and CO_2 methanation under uncertainty. *Fuel*, 2023 Jul 15; 344:127969.

- Dubucq, L., Contino, F., Rixhon, X., and Coppitters, D. (2023). How can carbon capture utilization and storage help decarbonizing the port of Antwerp? *Preprint*, (2024).

- Rixhon, X., Contino, F., Jeanmart, H, The atom-molecules dilemma of a whole-energy system with low local renewable potentials under uncertainty, *Preprint*, (2024).

- Rixhon, X., The atom-molecules dilemma of a whole-energy system with low local renewable potentials under uncertainty, Presentation at *Third EnergyScope Workshop*, Zurich, Switzerland, October 2024.

- Plas, E, Sousa, T, Contino, F, Jacques, P, The role of exergy-based taxation in reducing emissions and increasing efficiency: the case study of Belgium, *Preprint*, (2024).

2 Methods

2.1 Belgian whole-energy system model

In the next sections, the snapshot and pathway formulation for the Belgian energy system model are briefly described. Details about the model formulations are provided in [1].

2.1.1 Snapshot formulation

To represent the Belgian energy system, we utilized EnergyScope Typical Days [2] (Figure 1). EnergyScope TD is a model that optimizes both the investment and operational strategies of a 'whole'-energy system, which includes electricity, heating, mobility, and non-energy sectors. According to Contino et al. [3], a model qualifies as a 'whole-energy' system when it encompasses all energy sectors, including non-energy demands such as the production of plastics and other materials using feedstocks considered energy carriers, at the same level of detail. The model's hourly resolution over a year makes it well-suited for integrating intermittent renewables. Its formulation incorporates typical days and a reconstruction method that captures various time scales from hours to seasons while accounting for weekly wind patterns. This approach minimizes design impacts while significantly reducing computational time [1]. The model explores all possibilities by optimizing investment decisions and hourly operations throughout the year, with a computational time of less than a minute on a personal laptop. This feature was intentionally included in the model design to support uncertainty quantification and studies requiring numerous iterations. EnergyScope TD has been successfully applied to various national energy systems, including those of Switzerland [4], Belgium [5], and Italy [6].

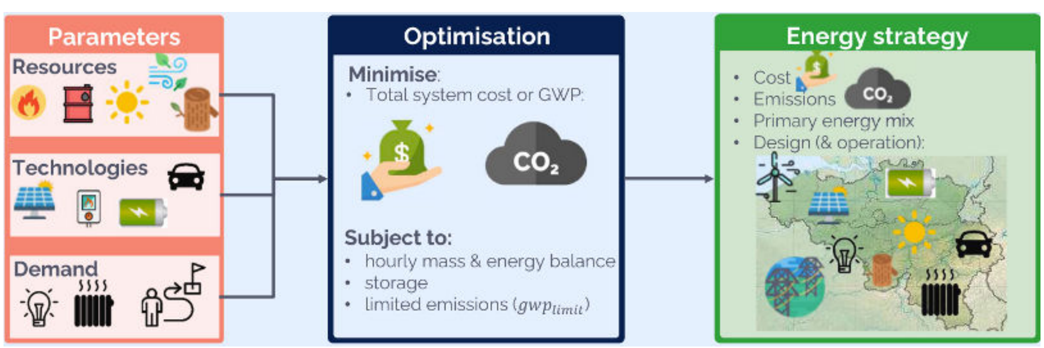

Figure 1: EnergyScope TD model representation [1]

2.1.2 Pathway formulation

While snapshot models offer insights into the energy system for individual years, they do not capture the dynamics inherent in investment strategies during a transition period. The pathway approach segments this transition into five-year intervals, optimizing the energy system for each specific year. This results in seven instances of EnergyScope TD, termed representative years, covering the 30-year transition from 2020 to 2050. To connect these representative years, we introduce additional constraints that account for investment changes between consecutive periods, considering societal inertia and evaluating both cost implications and emissions during the transition. Overall, these constraints are integrated into a linear framework, ensuring computational efficiency, with an approximate runtime of 14 minutes on a personal laptop (2.4 GHz Intel Core i5 quad-core).

Figure 2 illustrates the pathway concept. The proposed formulation is based on representative years selected every five years from 2020 to 2050. The period between two representative years is termed a "PHASE." For each of these seven years, the EnergyScope TD model is run using relevant data, such as energy demand, technology costs, and GHG emissions constraints. Consequently, a new dimension, "year," is added to all variables and parameters, except for the interest rate, which is assumed constant during the transition. This new dimension is essential to represent changes in technology and resource characteristics over the representative years.

2.1.3 Integration of CCS and CCU layers

The Belgian energy system in Energyscope is defined by an interaction of layers. To include the impact of the CO_2 valorization on the Belgian

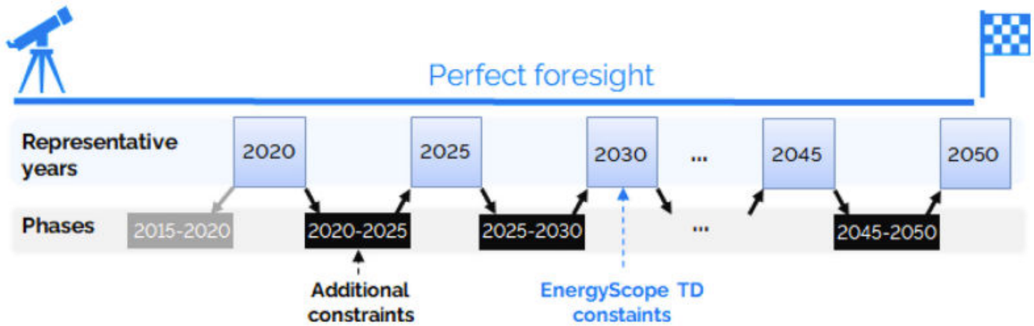

Figure 2: The pathway methodology relies on 7 representative years (blue boxes) where the model EnergyScope Typical Days (EnergyScope TD) is applied. Moreover, the formulation accounts for linking constraints (black boxes) and an initial condition (grey box). The overall problem is the pathway model [1].

energy system, we added a subsystem that characterizes CCS and CCU (Figure 3). This subsystem comprises the following technologies: post-combustion capture or oxy-fuel combustion capture technology, a Proton Exchange Membrane Electrolyser (PEME), a methanation unit, and a CO_2 storage technology. The CO_2 storage technology is designed to accommodate both temporary and permanent storage. In this subsystem, CO_2 from flue gas of industries is treated as a free resource, captured using one of the two capture technologies. Both capture technologies require electricity, and post-combustion capture additionally consumes high-temperature heat. The captured CO_2 then forms a layer that supplies the methanation unit and interacts with the CO_2 storage technology. Meanwhile, hydrogen is produced by the PEME or imported, and it is used exclusively by the methanation unit. This implementation creates a subsystem of interdependent technologies that exclusively interact with each other. As such, the captured CO_2

originates solely from industries, not from the atmosphere, and the hydrogen is only consumed in the methanation process, not by transportation. The compilation of this implementation in Energyscope will yield results on the energy system and economy.

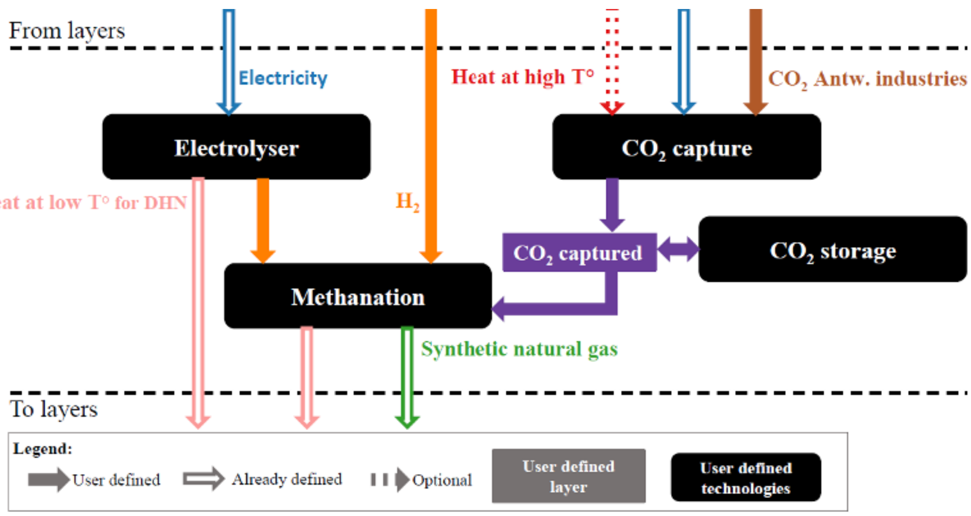

Figure 3: Overview of the implementation made on EnergyScope Typical Days, illustrated by CO_2 sources coming from industries in the port of Antwerp. The optional arrow represents the case where post-combustion capture (heat supply required) or oxy-fuel combustion capture is implemented (no heat supply required). Abbreviations: district heating network (DHN), Antwerp (Antw.).

2.1.4 Availability of CO_2

To estimate CO_2 emissions in the main industry clusters, two databases were utilized: the European Pollutant Release and Transfer Register (E-PRTR) and the Global Infrastructure Emission Database (GID). These databases provide plant-level data across various sectors. Due to missing data in both datasets, they were aggregated to create a comprehensive database. Some data is absent from the E-PRTR database. For instance, recent emissions from a significant steel industry, Thy-Marcinelle in Charleroi, are not reported. Consequently, some units are included in the E-PRTR but not in the GID, and vice versa. Additionally, the GID provides details such as the distinction between process and fuel emissions in the cement industry and the types of fuel used by power plants, while geological coordinates are only available in the E-PRTR. To enhance data completeness, the 2019 datasets were merged to fill in missing information while retaining common data. Ultimately, a comprehensive database was created by aggregating data from both sources. Notable differences in CO_2 emissions values were observed among common facilities. Since the E-PRTR is an official and regulated database, its values were prioritized; if unavailable, emissions data from the GID were used instead.

2.1.5 Carbon tax integration

The European Commission is currently promoting the implementation of a carbon tax. This tax could complement the VAT, leading to higher consumer prices. Some scholars argue that, in the future, carbon taxes should replace the VAT system. However, carbon taxes do not directly penalize inefficient processes, even though they are indirectly related. This presents a challenge, especially in regions where renewable resources are scarce. In such areas, efficient resource consumption remains crucial, even for non-emitting resources. Thus, while carbon taxes support environmental sustainability, a more comprehensive approach is needed—one that addresses both efficiency and emissions for effective environmental policies. An exergy-based tax could be a promising alternative. In a preliminary study, we evaluated the role of various tax systems—including carbon and exergy taxes—to identify the most suitable option for generating revenue and achieving the GWP target by 2050. Details of the methodology are provided in Appendix A.

2.2 Uncertainty quantification framework

In model-based studies, deterministic model parameters are typically assumed to be perfectly known and free from inherent variations. However, the operating environment is primarily characterized by parameters that are subject to uncertainty, such as the stochastic nature of solar energy, operation and maintenance costs, and energy demands. Additionally, in emerging markets like the CO_2 market, obtaining accurate market values presents a significant challenge [7]. Consequently, uncertainty in these parameters impacts performance, leading to stochastic behavior in system objectives.

The state-of-the-art method for propagating parameter uncertainties through a system model and quantifying the statistical moments of the model output—known as Uncertainty Quantification (UQ)—is Monte Carlo Simulation [7]. This method is robust (i.e., it always converges) and easy to implement; however, it requires a substantial number of model evaluations (ranging from 10^4 to 10^5) to achieve an acceptable level of convergence for the statistical moments. More computationally efficient alternatives include surrogate model construction methods, such as Gaussian Process Regression [8] and Polynomial Chaos Expansion (PCE) [9]. During the post-processing phase of the surrogate model—specifically, the quantification of statistical moments—PCE offers significant advantages, such as the analytic determination of statistical moments and Sobol' indices derived from the PCE coefficients [10].

In DRIVER, we developed and published an open-source, non-intrusive

Python framework for Uncertainty Quantification and optimization under uncertainty [11]. We integrated PCE and a novel robust design optimization technique [12] and made it user-friendly for connecting existing energy system models. The framework is fully documented online (Figure 4) and has been used in several engineering-based applications (25 citations in October 2024), also within DRIVER [13–15]. Details about the UQ technique are provided in [12].

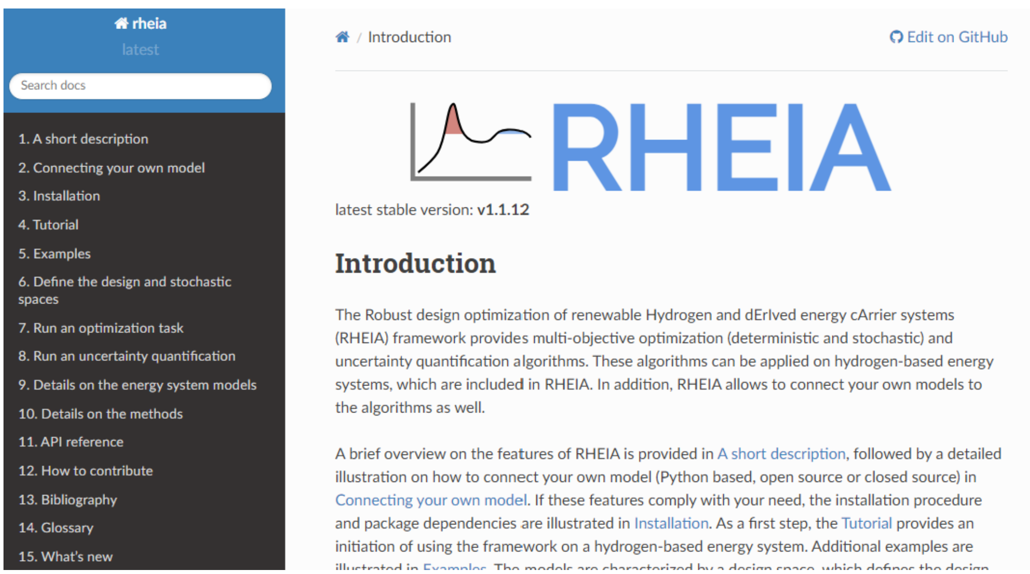

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Figure 4: Rheia is an open-source Python package for uncertainty quantification and optimization under uncertainty of energy systems. It is available on GitHub, fully documented and published in the Journal of Open Source Software [11]

3 Results

3.1 Impact of CO_2 utilization in the context of CCS and CCU on the Belgian energy system

In this first result, we assessed the role of CO_2 utilization within the frameworks of CCS and CCU on the Belgian energy system. We employed the snapshot Belgian energy system model (Subsection 2.1.1), which incorporates the integration of the CO_2 utilization layer (Subsection 2.1.3). As a case study, we focused on the industrial cluster in the Port of Antwerp as the source of CO_2 supply. This result is based on the work of Dubucq et al. [16], which includes further details.

Context. The port of Antwerp plays a crucial role in the Belgian economy, providing jobs for over 150,000 people and ranking as Europe's largest chemical cluster. However, its industrial activities contribute significantly to greenhouse gas (GHG) emissions. In response to Belgium's emissions reduction target of 47% by 2030 compared to 2005 levels, the Antwerp@C project has been initiated. This project's aim is to halve the port's CO_2 emissions by 2030 and achieve net-zero emissions by 2050 through Carbon Capture Utilization (CCU) and Storage (CCS). Under the supervision of Fluxys, a CO_2 transport network is planned to connect Belgium's main industrial clusters with those of neighboring countries. Antwerp, Zeebrugge, and Ghent have been selected to host CO_2 terminal infrastructures for offshore sequestration. Antwerp is linked to three major carbon capture and storage (CCS) projects: Northern Lights, CO_2TransPorts, and Antwerp@C. Northern Lights is a cross-border initiative that connects capture clusters across seven European countries.

CO_2 will be transported by ship to a Norwegian terminal for intermediate storage and then via pipeline for sequestration in saline aquifers in the North Sea. The first phase of this development is expected to be completed by 2024, targeting an annual storage capacity of 1.5 MtCO_2, with plans to expand to 5 MtCO_2 based on market demand. CO_2TransPorts aims to develop essential infrastructure for the efficient capture, transport, and storage of CO_2 across the ports of Antwerp, Rotterdam, and the North Sea Port. Other projects in France and the Netherlands, such as Aramis and Dartagnan, may also support the port of Antwerp through future collaborations.

Using the aggregated database (Subsection 2.1.4), 14.34 MtCO_2 were emitted by industries in the Port of Antwerp in 2019, accounting for 15.9% of Belgium's total CO_2 emissions. The target is to halve the port's CO_2 emissions by 2030, resulting in a reduction goal of 7.17 MtCO_2.

CO_2 capture technology performances. Based on the CO_2 concentration after capture and the recovery efficiency, we calculated the mass flow rates in the CO_2 capture systems. For post-combustion capture, this results in 7.24 Mt/y of CO_2-rich stream captured and a flue gas flow rate of 102.4 Mt/y after combustion. For oxy-fuel combustion capture, the derived mass flow rates include 7.55 Mt/y after the CO_2 compression and purification unit (CPU), with 18.7 Mt/y recirculated to the combustion chamber. To achieve an oxygen concentration of 30% in the oxidizer, the required mass flow rate of oxygen is 6 Mt/y.

Post-combustion capture is considerably more energy-intensive than oxy-fuel combustion capture due to the high energy demand for CO_2 separation (Figure 5). The heat required for regenerating the MEA solvent is particularly substantial, increasing the energy demand of post-combustion capture by approximately nine times. However, the decision to retrofit an existing plant with oxy-fuel combustion capture is not straightforward. Despite its lower energy requirement, oxy-fuel combustion remains less mature and more challenging to integrate into existing facilities. Additionally, the specific energy consumption of the Air Separation Unit (ASU) is sensitive to assumptions regarding the proportion of oxygen produced by this unit compared to production by electrolysers.

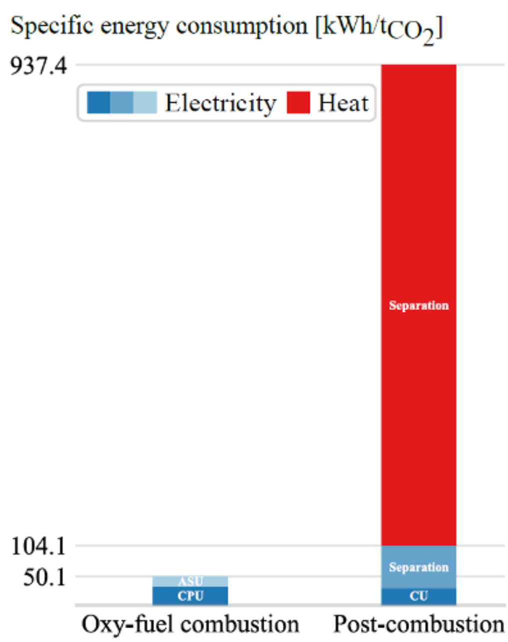


Figure 5: The breakdown of the specific energy consumption of the two capture technologies indicates how post-combustion capture is more energy-intensive than oxy-fuel combustion capture due to its heat requirement. Blue colours refer to electricity and red colour refers to heat. Abbreviations: air separation unit (ASU), compression and processing unit (CPU), compression unit (CU).

3.1.1 Full utilization of available CO_2 in CCU

Focusing on oxy-fuel combustion capture without hydrogen imports, utilizing all captured CO_2 results in the production of 28.17 TWh_{SNG} (Figure 6). This production requires 88.8 TWh_e, with 99.6% of that electricity consumed by the electrolysers. Consequently, the energy intensity of the CO_2 capture technology itself is relatively low. The substantial electricity demand from the electrolysers is comparable to the total final electricity consumption in 2021. On the other hand, 23.76 TWh_{th} is recovered for the District Heating Network (DHN) during water electrolysis and the methanation process.

The difference in energy production between the two capture technologies stems from two factors. First, the mass flow rate of the captured CO_2-rich stream is higher for oxy-fuel combustion capture, leading to a greater mass flow rate of hydrogen (H_2) and synthetic natural gas (SNG). Second, post-combustion capture requires more electricity and heat per ton of CO_2. As a result, despite its lower energy needs for capture, oxy-fuel combustion capture ultimately produces more energy overall.

When accounting for the projected hydrogen imports by 2030 (11 TWh), both electricity consumption and low-temperature heat production decrease. The optimization performed by ESTD favors maximizing hydrogen imports, as importing hydrogen is more cost-effective than producing it via electrolysis, given Belgium's limited renewable energy production capacity. The scenario depicted in darker colors represents this optimized case. However, questions remain about the feasibility of generating such a large surplus of electricity by 2030. Furthermore, ESTD's projections indicate a required electrolyser capacity of 10 GW, which may be challenging to achieve by

2030.

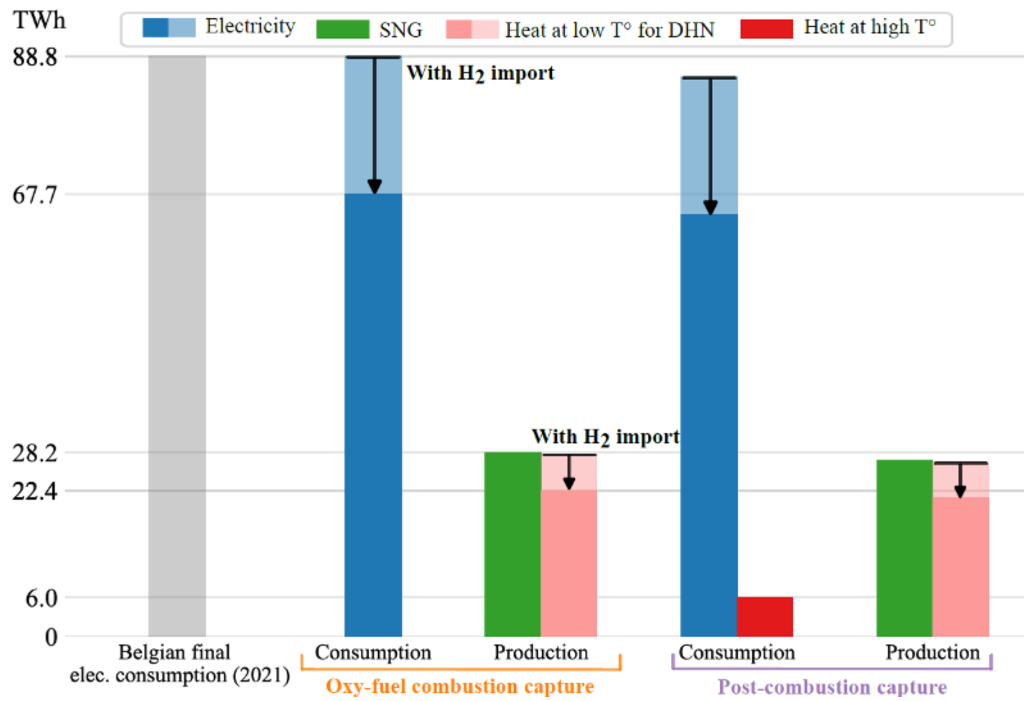


Figure 6: The energy production and consumption of a power-to-gas system supplied with all the captured CO_2 of the industries of the port of Antwerp show the massive electricity consumption by the electrolysers. Abbreviations: synthetic natural gas (SNG), district heating network (DHN), electricity (elec.).

An overview of the electricity mix resulting from this substantial electricity demand is shown in Figure 7. Compared to the scenario without CCU implementation in the Port of Antwerp, a significant increase in total electricity production is observed, driven by the previously described energy requirements. This increase is achieved by expanding photovoltaic (PV) capacity, as well as ramping up industrial gas Combined Heat and Power (CHP) and Combined Cycle Gas Turbine (CCGT) production.

Oxy-fuel combustion capture results in lower electricity production from CHP compared to post-combustion capture, as the latter has a heat demand that is supplied by CHP. This difference is partially compensated by a higher output from CCGTs in the case of oxy-fuel combustion capture.

The PV electricity production leads to the installation of the maximum feasible capacity, totaling 59.2 GW. With Europe targeting 600 GW of installed PV capacity by 2030, this estimate for Belgium represents nearly 10% of the European goal, which is notable given Belgium's small size and dense population. Wind turbine installations also reach their upper limits in all three scenarios (10 GW for offshore and 6 GW for onshore wind turbines), leading to a slight increase in annual electricity generation compared to the reference case. Additionally, electricity imports are maximized.

These changes in the energy system result in additional investments and costs. The increase in total annual costs is estimated at 6.4 billion €/year (a 14.8% increase) for oxy-fuel combustion capture and 6.5 billion €/year (a 14.9% increase) for post-combustion capture. These costs represent about 1.2% of Belgium's gross domestic product in 2022. Thus, the additional costs associated with producing synthetic natural gas (SNG) while halving the CO_2 emissions from the Port of Antwerp are relatively modest.

A closer look at these costs highlights the key differences in the energy system (Figure 8). First, a significant increase in the imports of hydrogen, natural gas, and renewable methanol contributes the most to the added expenses. Imports are favored as they are cheaper than domestic production of these energy carriers. Second, as previously discussed, there is an increase in the installed capacities of PV panels, industrial gas-fueled CHP plants,

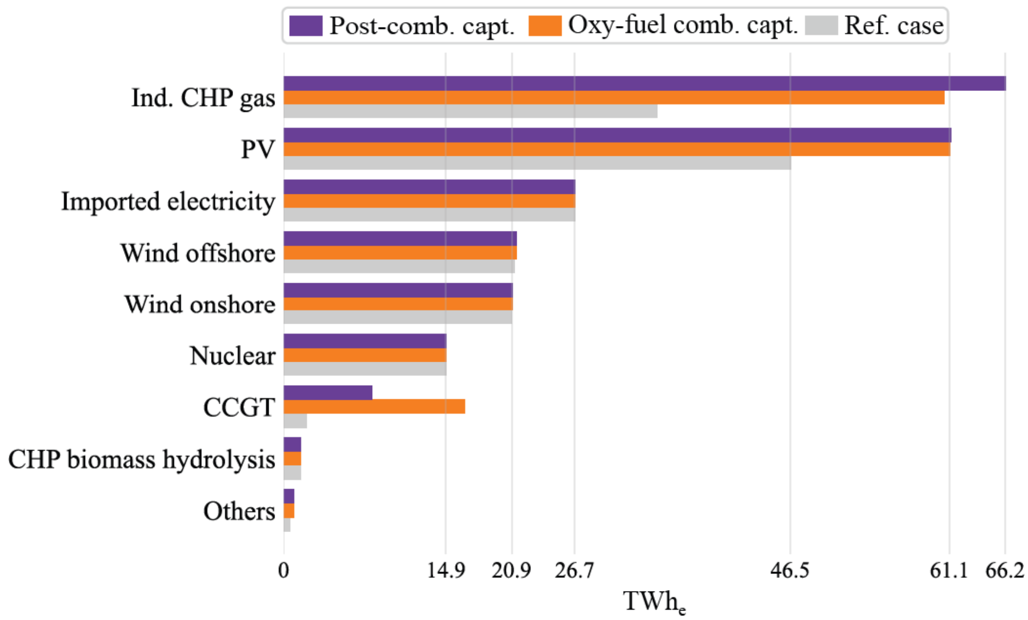


Figure 7: The comparison of the electrical mix with and without power-to-gas in the port of Antwerp illustrates how the important additional electricity requirement is produced, when all the captured CO_2 is used. Abbreviations: combustion (comb.), capture (capt.), industrial (ind.), combined heat and power (CHP), photovoltaic (PV), combined cycle gas turbine (CCGT).

the technologies supporting the Power-to-Gas (PtG) system, and high-value chemical (HVC) production using methanol, leading to higher associated costs. The District Heating Network (DHN) and electricity grid also incur additional costs. The electricity grid requires reinforcement due to the integration of more intermittent renewable energy, primarily from PV panels. The DHN costs scale with the capacity of technologies that produce the corresponding heat. Consequently, the heat generated for the DHN by electrolysers and the methanation process necessitates a larger DHN, resulting in extra costs. This increase in heat production outweighs the reduction in heat generated by heat pumps. Gas and CO_2 storage costs increase due to higher production of gas, captured CO_2, and low-temperature heat for the DHN. Without storage, the installed capacity of a technology matches its peak production, leading to oversizing and higher costs. Storage technologies help buffer peak production, reducing the required installed capacity. Interestingly, the opposite trend is seen for waste boilers; their installed capacity is larger than in the reference case, even though the annual energy balance remains the same. This means that the capacity of waste boilers is oversized, which reduces the need for high-temperature thermal storage. As a result, the share of high-temperature heat generated by gas boilers increases, while that from biomass boilers decreases. This shift occurs because most biomass is allocated to methanol production. Methanol production rises significantly with PtG in the port, as methanol replaces oil in HVC production. Consequently, in the reference case, the high-temperature heat generated by biomass boilers is now predominantly produced by gas boilers, with gas boilers also compensating for reduced direct electricity heating.

3.1.2 Partial utilization of available CO_2 in CCU

Given the immense impact of the hydrogen production to convert the available CO_2 in SNG, we assess a scenario where the projected quantity of hydrogen available for CO_2 hydrogenation in 2030 is equal to the amount of hydrogen available through imports and local production—estimated at 11 TWh_{H2} from imports and 0.65 TWh_{H2} from domestic production, resulting in a total of 11.65 TWh_{H2}. Hence, a portion of the captured CO_2 will react with this hydrogen, while the remainder will be sent for long-term storage. This approach aims to assess whether this scenario is more feasible than

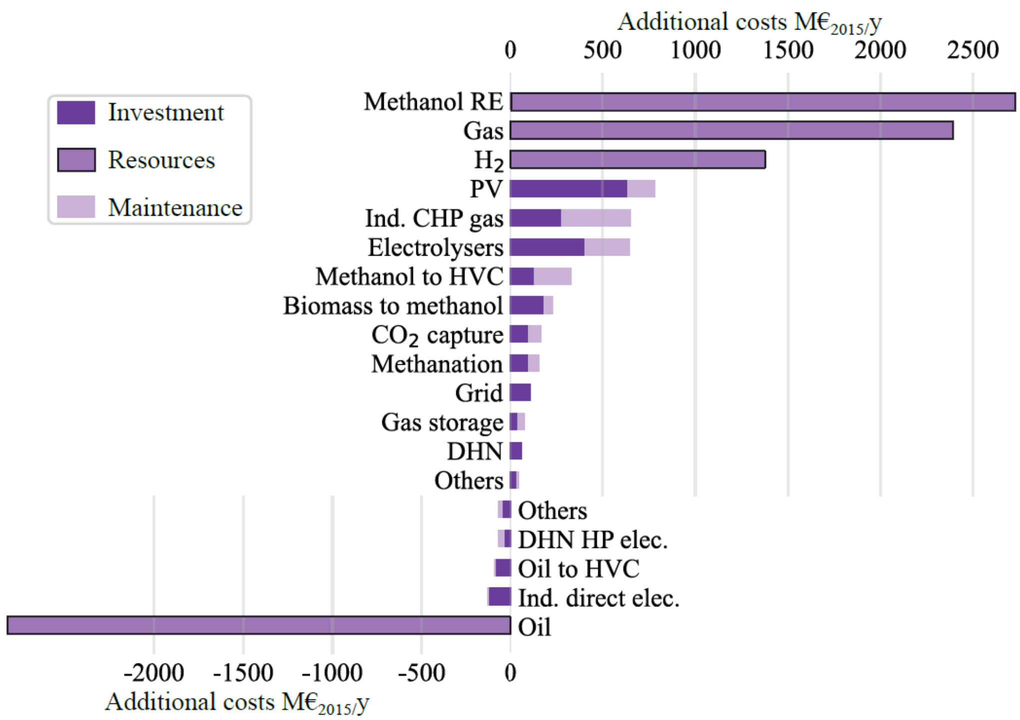


Figure 8: The breakdown of the additional costs compared to the scenario without Power-to-Gas (PtG) highlights the sources of the 6.5 billion euro/year increase in total costs. Abbreviations used include: renewable energy (RE), photovoltaic (PV), industrial (ind.), combined heat and power (CHP), heat pump (HP), high-value chemicals (HVC), and district heating network (DHN).

utilizing all the CO_2 in a CCU context.

Since post-combustion capture requires more specific energy than oxy-fuel combustion capture, it is more critical in terms of energy efficiency. Therefore, only post-combustion capture is considered for the following results. While the results with oxy-fuel combustion capture would be similar, the differences in specific energy consumption and the slightly higher quantity of CO_2-rich stream captured with oxy-fuel capture would lead to marginally more CO_2 being stored, as well as minor differences in energy consumption and production. As a reminder, 7.2 $MtCO_2$ is captured with this system. Of this, 5.3 $MtCO_2$ (73.6%) will be stored, and 1.9 $MtCO_2$ (26.4%) will be utilized, resulting in the production of 7.19 TWh_{SNG} through methanation.

With 11 TWh_{H2} imported, domestic hydrogen production decreases by 98% compared to the full utilization scenario (Figure 9). Consequently, even though the energy requirement for CO_2 capture remains constant, a significant reduction in electricity consumption (97%) is anticipated, as electrolysers are the primary contributors to electricity usage. On the other hand, total energy production naturally decreases from 43.7 TWh to 7.5 TWh.

As outlined before, the energy requirement for the CO_2 capture is minor compared to the electrolysers consumption. Therefore, the changes in the electricity mix are relatively small when the quantity of used CO_2 matches the projections of available hydrogen for the methanation (Figure 10).

The quantity of available gas is nearly identical between the two cases (Figure 11). However, natural gas imports are lower in the partial utilization case, as SNG production through methanation fills the gap. The slight increase in gas supply supports the combined heat and power (CHP) plants and combined cycle gas turbines (CCGTs). As natural gas imports decrease by 6.82 TWh, greenhouse gas (GHG) emissions from gas combustion are also lower in the partial utilization case, despite a slightly higher availability of gas.

In conclusion, this scenario is more realistic in terms of energy consumption; however, it relies heavily on substantial estimates of future hydrogen imports. Currently, Europe's installed electrolyser capacity is approximately

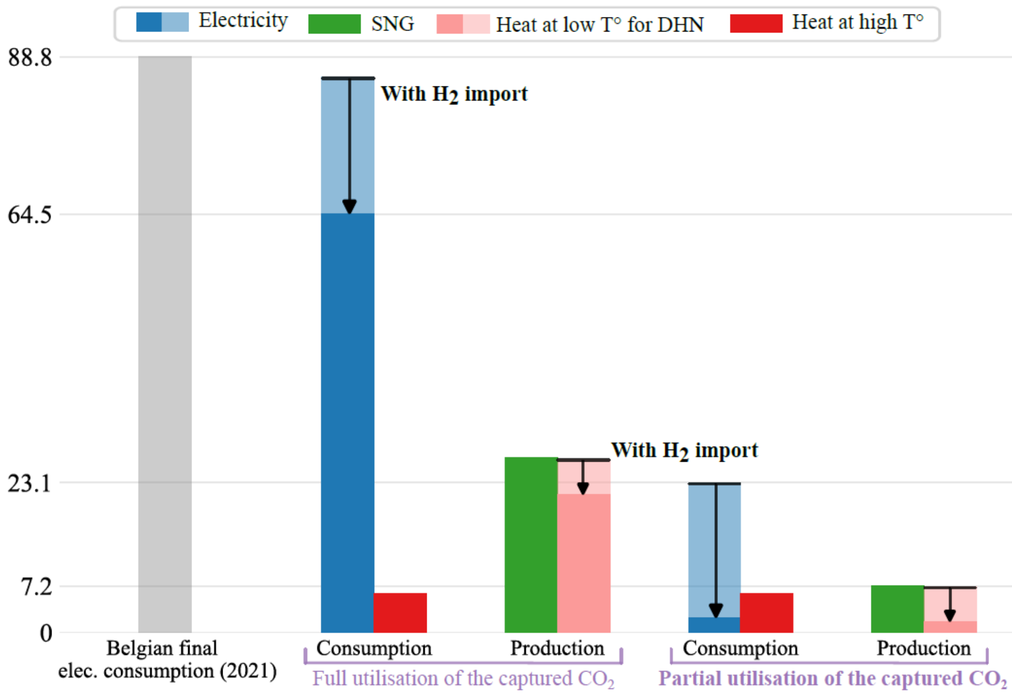


Figure 9: Comparison of the energy consumption and production between using 26.4% (1.9 $MtCO_2$) of the captured CO_2 (on the right) and using all the captured CO_2 (on the left). The capture technology used is the post-combustion capture. Abbreviations: synthetic natural gas (SNG), district heating network (DHN), electricity (elec.).

160 MW. With Belgium anticipating an electrolyser capacity of 150 MW by 2030, significant investments will be necessary to meet this objective.

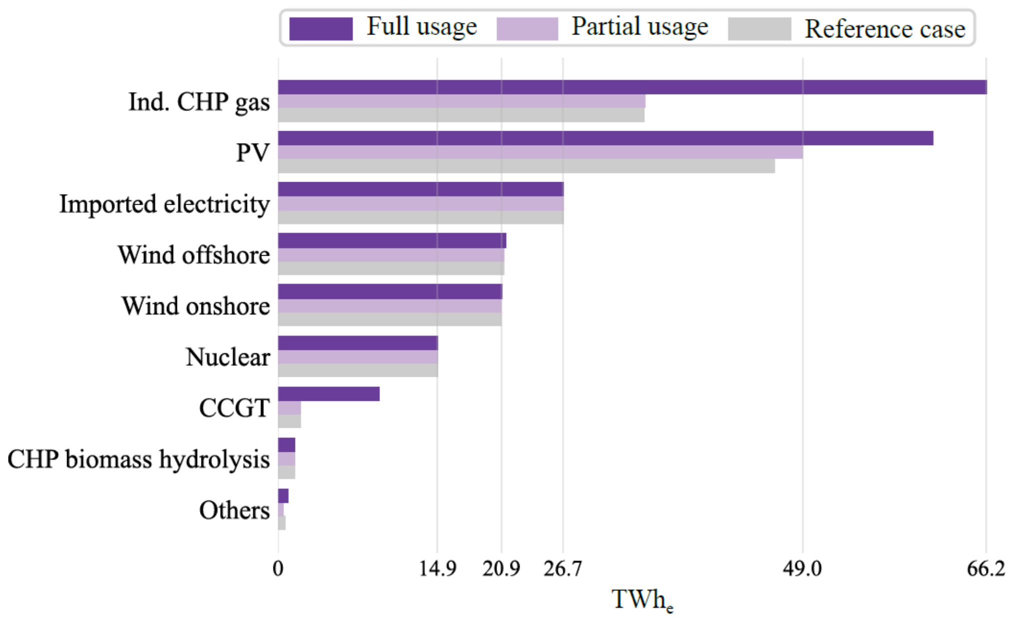
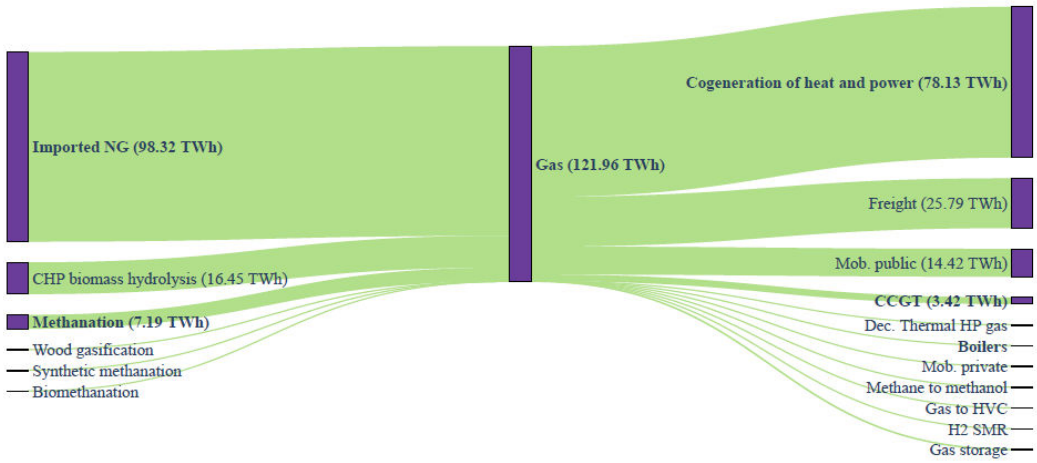
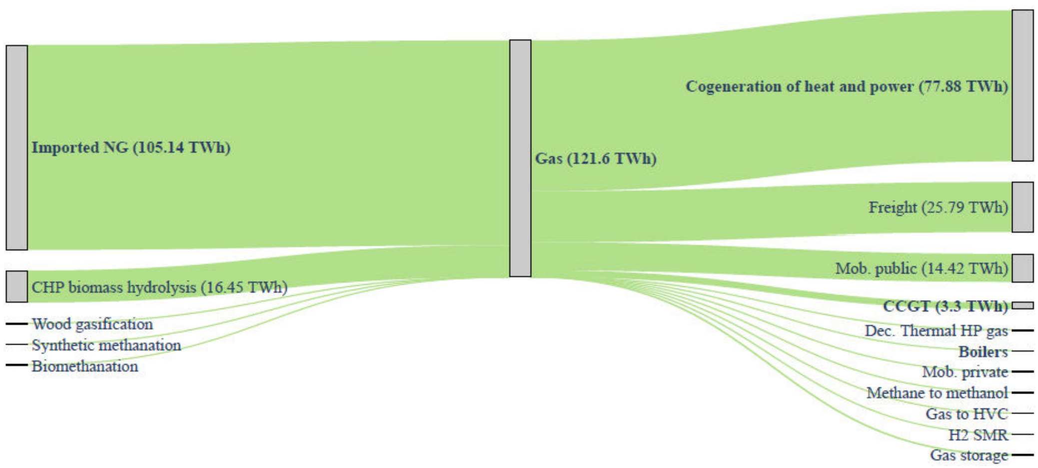


Figure 10: Comparison of the electrical mix between a partial utilisation, a full utilisation of the captured CO_2 and the case with no power-to-gas in the port of Antwerp. The capture technology used is the post-combustion capture. Abbreviations: photovoltaic (PV), industrial (ind.), combined heat and power (CHP), combined cycle gas turbine (CCGT).



(a) Case with partial utilisation of the captured CO_2 in the port with post-combustion capture.



(b) Case without power-to-gas in the port of Antwerp.

Figure 11: The comparison of the gas flows between case (a) and (b) indicates a decrease of the natural gas import with power-to-gas in the port of Antwerp. Gas naming refers to either natural gas or synthetic natural gas. Names in bold emphasise the differences between the reference case and the case with the partial utilisation of the captured CO_2. Abbreviations: imported (imp.), natural gas (NG), combined heat and power (CHP), combined cycle gas turbine (CCGT), decentralised (dec.), heat pump (HP), mobility (mob.), high-value chemicals (HVC), steam methane reforming (SMR).

3.2 Role importing carbon-based electrofuels

As illustrated in the previous section (Subsection 3.1), even when local valorization of CO_2 is prioritized, substantial imports of e-methane are required. This section examines the role of importing renewable molecules, such as e-methane, from abroad within the Belgian energy system. Specifically, it analyzes the factors driving the need for these electrofuel imports. This assessment adopts a strictly techno-economic perspective, focusing on cost-based optimization. Furthermore, given the significant uncertainties related to the import of these fuels, we consider technical, economic, availability, and demand-related uncertainties throughout the transition.

3.2.1 Impact on the total transition cost

Optimizing the energy transition using the pathway model (Subsection 2.1.2) and assessing the uncertainty on the optimized solution (using UQ as described in Subsection 2.2), the total transition cost stretches between 660 b€ and 2050 b€(Figure 12).

Table 1 shows that the uncertainty on the cost of purchasing electrofuels is the most influential parameter affecting the total transition cost for the Belgian energy system. Renewable electrofuels are consistently imported, albeit to varying extents depending on the sample. For instance, in the reference case without the availability of nuclear SMR, imported electrofuels are projected to account for 152.9 TWh (i.e., 41% of the primary energy mix) by 2050, with an average purchasing cost of 93 €/MWh. Over the entire transition period, this results in a cumulative operational expenditure (OPEX) of 273 billion euros, representing 25% of the total transition cost. Given the relatively wide uncertainty range (i.e., from -30.8% to +24.0% by

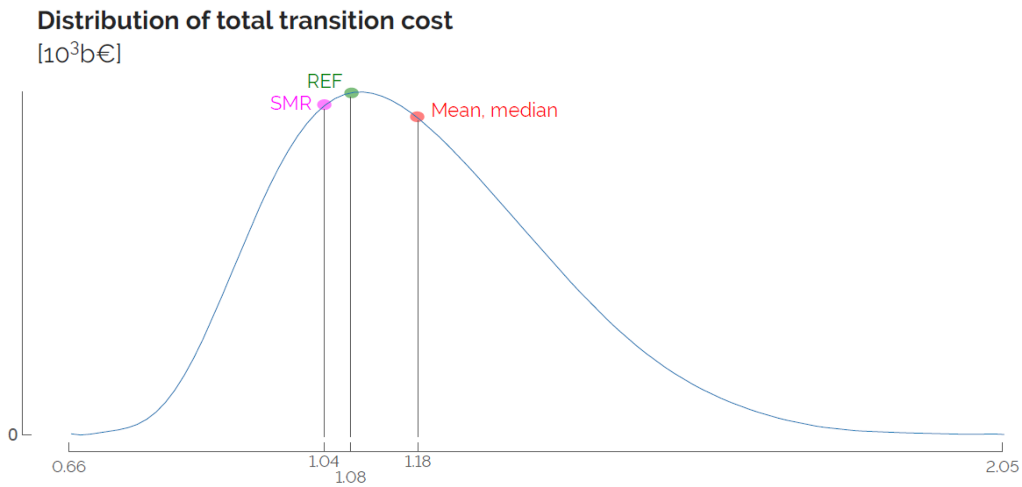


Figure 12: The distribution of the total transition cost reveals that the mean cost, $\mu = 1.18 \times 10^3$ b€, is slightly higher than the median ($P_{50} = 1.16 \times 10^3$ b€) and the nominal case costs of 1.08×10^3 b€ and 1.04×10^3 b€ for the REF and SMR cases (SMR considers the availability of nuclear Small Modular Reactors from 2040 onwards), respectively. Additionally, with a standard deviation of $\sigma = 197$ b€, the 95% confidence interval is approximately $[0.8; 1.6] \times 10^3$ b€.

2050) and the substantial share of total demand (between 53% and 60%), the uncertainty on the industrial energy use demand (EUD) emerges as the second most impactful parameter. As a key factor in the annualization and salvage value of assets, the discount rate has a Sobol' index of 12%. Additionally, the cost of purchasing fossil fuels is also a significant parameter influencing the variation of the total transition cost. However, due to the ambitious CO_2 budget, the urgent need to phase out fossil fuels reduces their impact compared to renewable alternatives.

Table 1: Total Sobol' indices of the four most-important uncertain parameters over the total transition cost.

Parameter	Ranking	Sobol' Index
Purchase electrofuels	1	46.8%
Industry end-use demand	2	23.2%
Discount rate	3	12.0%
Purchase fossil fuels	4	5.7%

3.2.2 Drivers of the need of importing electrofuels

Performing UQ (Subsection 2.2) on the pathway whole-energy system model (Subsection 2.1.2), which considers uncertainties in the techno-economic parameters of technologies, resource availabilities, and energy demands, we quantify the uncertainty around renewable electrofuel imports throughout the transition. While overall trends show an increase, variations exist between different energy carriers (Figure 13). E-methane, a renewable alternative to fossil methane, starts to substitute fossil methane as early as 2025 in some scenarios, reaching 163 TWh. The demand for e-methane grows progressively through the transition, primarily to supply industrial combined heat and power (CHP) systems and boilers. E-hydrogen quickly becomes the predominant hydrogen source in the system, with median and maximum values of 13.0 TWh and 42.1 TWh in 2050, respectively. It is primarily used in the mobility sector. Fuel cell trucks often become the preferred option. However, in some scenarios, fuel cell cars and buses fully replace battery electric vehicles (BEVs) and compressed natural gas (CNG) buses by 2050. In some future scenarios, local production of methanol via the methanation process contributes up to 17.8 TWh, or 33% of the total methanol supply. Imported e-ammonia rapidly becomes cost-competitive with its fossil counterpart, initially replacing fossil ammonia and the Haber-Bosch process. While its primary role is to meet a relatively small Non-Energy Demand (NED) of about 10 TWh by 2050, its import levels vary mainly based on the need for ammonia-based combined-cycle gas turbines (CCGT) as a flexible electricity production option. Starting in 2035, e-ammonia shows the greatest uncertainty among the four considered electrofuels, with an interquartile range (IQR) of around 50 TWh. In extreme scenarios, e-ammonia becomes the most imported electrofuel, reaching up to 167 TWh, or 45% of the total primary energy mix. Similarly, e-methanol quickly becomes the preferred option for meeting methanol demand, though alternatives like biomass-to-methanol contribute about 5% of average demand. Non-Energy Demand for e-methanol accounts for roughly 3% of total methanol consumption. Variability in e-methanol imports is driven by its role in the industrial production of high-value chemicals (HVC) through the Methanol-to-Olefins (MTO) process, which represents 95% of total consumption. The remaining 2% is used to supply the freight transport sector via boats and trucks.

In the next step, we assess the space of uncertainties. Trend lines for key parameters are plotted for the imports of electrofuels in 2050. The year 2050 is selected as it represents the peak of electrofuel imports during the transition. Alongside each parameter, its Sobol' index is shown relative to the output of interest.

For e-methanol imports, industrial EUD is the dominant factor, with a Sobol' index of approximately 80% (Figure 14). This is due to its own Non-

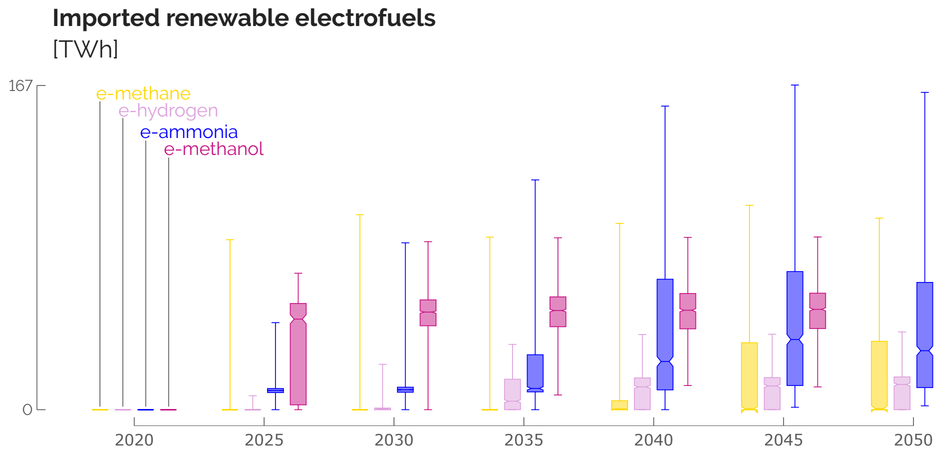


Figure 13: Distribution of the imported renewable electrofuels over the transition. Starting from no electrofuel in 2020, their respective import rises progressively along the transition at different growth rates and with different ranges of values.

Energy Demand (NED) and, more importantly, because the model selects e-methanol as the low-emission alternative to meet the substantial NED of high-value chemicals (HVC). Thus, a lower industrial demand results in reduced e-methanol imports, and vice versa.

The sensitivity analysis for e-hydrogen highlights its dependence on various parameters, especially those related to the transport sector (Figure 15). E-hydrogen is mainly used in fuel cell (FC) trucks, followed by FC cars and buses to a lesser extent. The adoption of fuel cell engines in trucks contributes, on average, to 63.5% of total road freight transport, which significantly affects the level of e-hydrogen imports. As a result, lower CAPEX for fuel cell engines leads to increased e-hydrogen imports. Similarly, the costs of purchasing electrofuels influence e-hydrogen imports, with biofuel costs emerging as the third most influential factor. Biodiesel trucks are the pri-

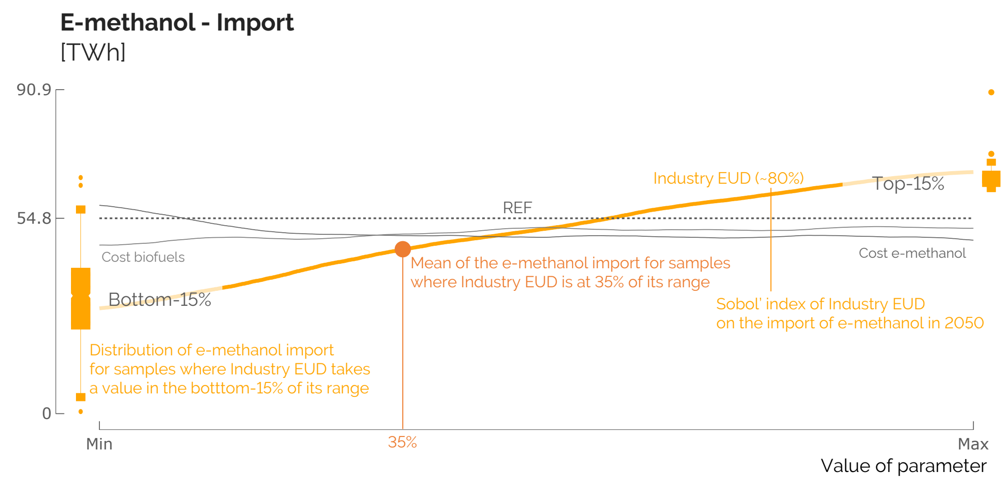


Figure 14: Trend lines of the key parameters (and their Sobol' index) on the import of e-methanol in 2050. Around these lines, box plots point out the distribution of the output of interest for the extreme values (either bottom-15% or top-15%) of some parameters. The grey dashed line gives the value of the output of interest in the REF case.

mary alternative to FC trucks, providing an average of 27.6% of road freight transport. Additionally, CNG buses dominate public road transport with 34.9%, followed by FC buses (11.2%), competing with biodiesel and hybrid biodiesel buses, which account for 27.8% and 26.1%, respectively. Finally, the CAPEX of electric vehicles is another notable parameter. The cheaper BEVs become, the more competitive they are compared to FC cars, which make up about 13.7% of total passenger mobility on average.

The installation of nuclear Small Modular Reactors (SMR) drastically reduces e-ammonia imports (Figure 16). Since ammonia CCGTs are the largest consumers of ammonia by the end of the transition, low-emitting and cheaper electricity produced by SMR (40 versus 151 €/MWhelec) substitutes these CCGTs. With higher costs of electrofuels, e-ammonia imports

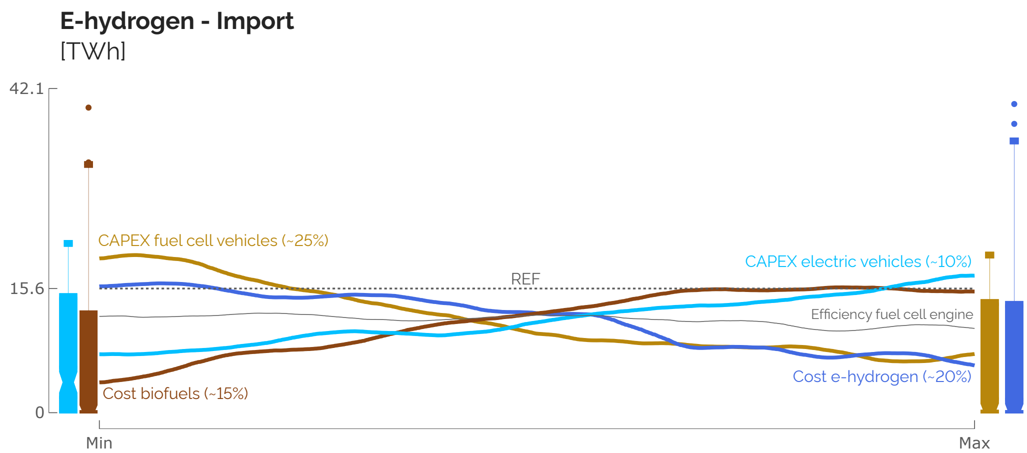


Figure 15: Trend lines of the key parameters (and their Sobol' index) on the import of e-hydrogen in 2050. Around these lines, box plots point out the distribution of the output of interest for the extreme values (either bottom-15% or top-15%) of some parameters. The grey dashed line gives the value of the output of interest in the REF case.

can drop to as low as 2.0 TWh, a 95.4% reduction compared to the REF case. Additionally, with a 12% Sobol' index, the cost of imported renewable electricity in 2050, which competes directly with e-ammonia CCGTs, also affects ammonia demand, particularly when these electricity costs are low.

Industrial EUD has the greatest impact on e-methane imports (Figure 17). This parameter directly influences the demand for industrial high-temperature heat, where industrial gas CHP and, to a lesser extent, gas boilers provide, on average, 25.6% and 6.1% of total production, respectively. Among the less impactful parameters, SMR still plays a significant role. If deployed, SMR generates abundant low-emission electricity, allowing industrial electric heaters to replace, sometimes entirely, gas-based alternatives. Additionally, high availability of local biomass reduces e-methane imports,

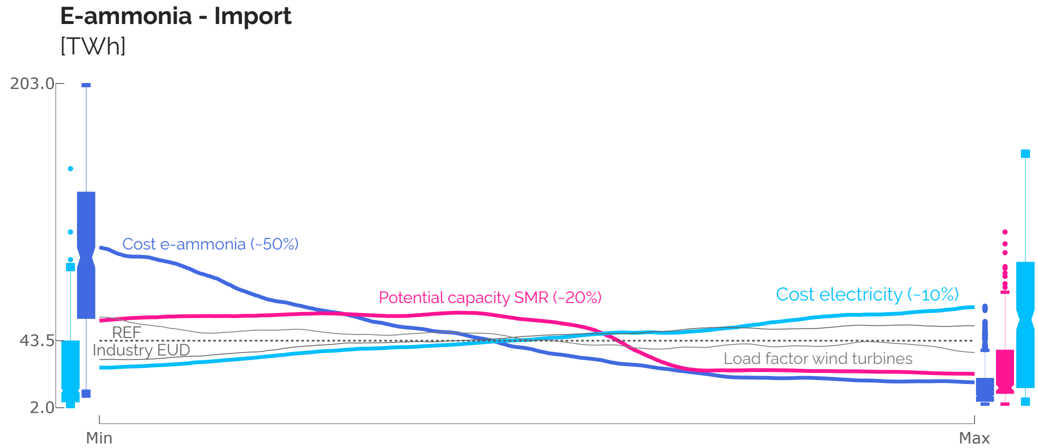


Figure 16: Trend lines of the key parameters (and their Sobol' index) on the import of e-ammonia in 2050. Around these lines, box plots point out the distribution of the output of interest for the extreme values (either bottom-15% or top-15%) of some parameters. The grey dashed line gives the value of the output of interest in the REF case.

as it supports bio-hydrolysis for methane-equivalent gas production.

Interestingly, the costs of purchasing electrofuels and fossil fuels show opposite correlations with the amount of e-methane imported. By 2050, more expensive electrofuels lead to higher e-methane imports, while cheaper electrofuels result in greater fossil methane imports. Within the techno-economic optimization framework of EnergyScope, if electrofuels are costlier, the system will generally import fewer of them—especially e-ammonia, which is mainly used in CCGTs. Given the CO_2 budget for the transition, the system shifts toward more efficient technologies, such as industrial methane-CHP, to replace e-ammonia CCGTs for electricity production. Initially running on fossil gas, these CHPs consume more e-methane by 2050. Conversely, if electrofuels are cheaper, the system imports more of them, particularly e-ammonia. This allows the use of more emitting but less costly resources while adhering to the CO_2 budget, such as coal in industrial boilers, which produces an average of 24% of high-temperature (HT) heat in 2050. These scenarios indicate that if emissions decrease more sharply in the early transition stages, the model may opt for highly emitting resources (e.g., coal) while staying within the CO_2 limits. This leads to reduced investments in methane CHP and, consequently, lower e-methane imports as more renewable electricity is generated via e-ammonia CCGTs, and more HT heat comes from industrial coal boilers.

Although coal use in Belgium by 2050 may seem unlikely, the model considers it if the CO_2 budget permits. Regarding fossil fuel costs, this parameter primarily impacts fossil NG imports, given its versatility in the whole-energy system. If NG becomes more expensive, imports decrease, leading to reduced investments in methane-CHP and boilers, ultimately decreasing the demand for e-methane by 2050.

3.3 Impact of carbon tax

In Appendix A, Figure 6 illustrates the impact of a carbon tax, showing how variations in CO_2 prices influence emissions and exergy efficiency. As expected, the carbon tax significantly reduces emissions but does not achieve the same level of exergy efficiency as exergy-based tax systems.

Table 2 provides a comparative analysis of different tax systems, assessing the effectiveness of an exergy-based tax versus a carbon tax. Based on the study's criteria for a sustainable tax system—generating sufficient revenue (€10 billion), improving exergy efficiency, and maintaining low emissions—a carbon tax alone falls short. As the adoption of alternative energy and

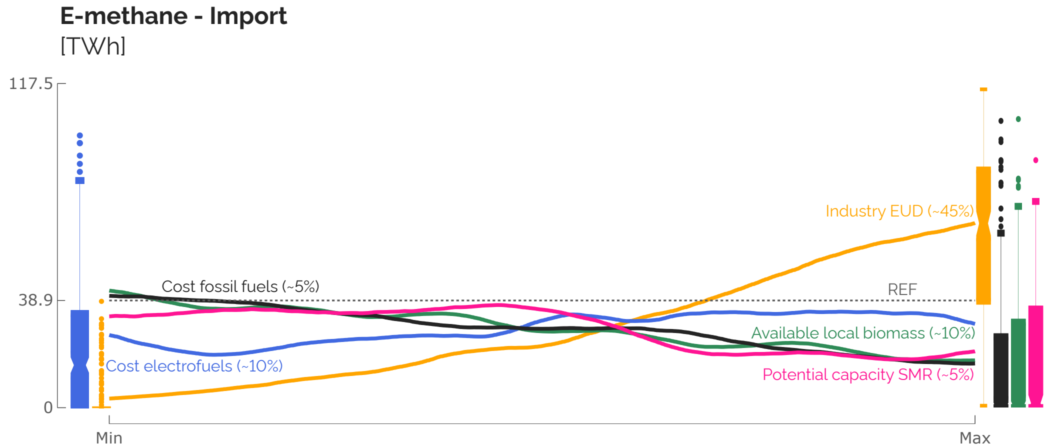


Figure 17: Trend lines of the key parameters (and their Sobol' index) on the import of e-methane in 2050. Around these lines, box plots point out the distribution of the output of interest for the extreme values (either bottom-15% or top-15%) of some parameters. The grey dashed line gives the value of the output of interest in the REF case.

efficiency technologies grows, firms and individuals can reduce emissions, leading to a diminishing carbon tax base. Consequently, integrating the carbon tax with another tax system becomes necessary to maintain target revenue levels.

Currently, Belgium's approach involves combining the carbon tax with Value Added Tax (VAT) to support revenue generation and emission reduction. However, achieving both robust revenue and low emissions is possible by significantly enhancing exergy efficiency (see Table 2) through a combination of a carbon tax and an exergy loss tax.

More details on the results are available in Appendix Appendix A. Note that this is a preliminary work that will be used as a basis for future work.

4 Conclusion

This deliverable evaluates the potential of valorizing captured CO_2 in a CCU context into e-methane and its impact on the Belgian energy mix. Second, it indicates the main drivers of the demand related to e-methane and other electrofuels in the Belgian energy system. Finally, it provides a first indication on the role of a carbon tax on the Belgian energy system.

To valorize the captured CO_2, two scenarios are considered: one where all captured CO_2 is utilized for methanation, and another where only the CO_2 required for reaction with available hydrogen is used, with the surplus permanently stored underground. As a case study, it has been applied to the industrial cluster at the Port of Antwerp. The full utilization scenario involves additional costs of €4.9 to €8.4 billion (2015) per year, reflecting an 11% to 19% increase compared to a scenario without CCU in the port of Antwerp. This expense represents approximately 1.2% of Belgium's 2022 GDP. The scenario produces 21.8 to 32 TWh of synthetic natural gas (SNG) and 17.1 to 25.3 TWh of thermal energy, requiring up to 11 TWh of hydrogen imports, translating to electricity consumption of 48.8 to 80.3 TWh and a heat demand of 4.9 to 7 TWh. This would necessitate 59.2 GW of photovoltaic (PV) capacity and 10 GW of electrolysers—an ambitious target, given Europe's current electrolyser capacity of 160 MW. In contrast, the partial utilization scenario produces 5.18 to 9.1 TWh of SNG using 8 to 14 TWh of imported hydrogen and 0.47 to 0.83 TWh produced domestically, depending on hydrogen demand ratios. This scenario uses 16.3% to 41.6% of the captured CO_2, leading to reduced electricity needs, more feasible PV installation capacities, and lower imported natural gas compared to the reference case. Thus, partial CO_2 utilization alongside storage appears more practical.

Alongside local production, Belgium is expected to import carbon-based electrofuels in the near future. One potential "unicorn" solution is the early import of renewable electrofuels, assumed to be carbon-neutral and widely available. The substantial uncertainty surrounding the cost of these imports makes this the most significant factor influencing the total transition cost, with a variability of around 45%. The uncertainty quantification analysis further identifies key drivers for importing renewable electrofuels by 2050. Beyond purchasing costs—where lower costs drive higher imports—it indicates that nuclear SMR availability primarily impacts e-ammonia imports by substituting ammonia CCGT, the largest consumer of e-ammonia. This, in turn, reduces e-methane imports by lowering demand for gas CHP and boilers. Imports of e-hydrogen and e-methanol are influenced by competition from alternative transport technologies and industrial demand, respectively. In conclusion, the need for electrofuels during the transition suggests that ongoing investment in transport infrastructure is wise. For example, Fluxys, Belgium's gas network operator, has already committed around €1.3 billion in investments by 2032 to support this transition. Investing in electrofuel infrastructure could also help mitigate the risks associated with the potential unavailability of unicorn technologies like nuclear SMR by mid-century.

Finally, a preliminary study (Appendix A) illustrates the impact of a carbon tax significantly reduces emissions but does not achieve the same level of exergy efficiency as exergy-based tax systems. Based on the study's criteria for a sustainable tax system—generating sufficient revenue (€10 billion), improving exergy efficiency, and maintaining low emissions—a carbon tax alone falls short. Consequently, integrating the carbon tax with another tax system becomes necessary to maintain target revenue levels. This work will be used as a basis in future work.

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Appendix A The role of taxation strategies in reducing emissions and increasing efficiency

The role of exergy-based taxation in reducing emissions and increasing efficiency: the case study of Belgium

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July 2024

1. Introduction

The Intergovernmental Panel on Climate Change (IPPC, 2023) has repeatedly called for policymakers to make impactful decisions to mitigate climate change. Human activities, primarily through the emission of greenhouse gases, have unequivocally caused global warming, with global surface temperatures reaching 1.1°C above pre-industrial levels (1850-1900) in the decade from 2011 to 2020 (IPPC, 2023). Global greenhouse gas emissions have continued to rise, driven by unsustainable energy use, land use and land-use changes, lifestyles, and patterns of consumption and production. Despite the implementation of various policies, the projected emissions for 2035 at best remain constant rather than decreasing (IPPC, 2023).

To ensure the survival of humanity on Earth, energy policies need to be more ambitious. As highlighted by J. Ghosh, rethinking tax structures is essential for financing a transformation towards sustainability. Belgium, for instance, currently collects €8.5 billion annually through energy taxes (Eurostat) without specifically promoting the energy transition (Commission, 2020). Changing the tax system, as suggested by Szargut (2002), could alter the distribution of taxes without necessarily increasing the total tax burden. Tax collection can be rethought to encourage the reduction of products with a significant environmental impact.

Currently, international income taxes generally penalize the positive effects of human activity, through a tax on Value-Added (VAT) for example. Szargut (2002) proposes introducing taxes that target the negative effects of human activity, particularly those that harm the natural environment. Following this idea, this thesis proposes different taxes that target the loss of exergy, a measure of energy quality, thereby encouraging more sustainable energy use and reducing environmental degradation.

Currently the European Commission is promoting the carbon tax. That tax could be used as a complement to the VAT, resulting in higher consumer prices. In the future, some scholars argue that carbon taxes should replace the VAT system (Prasad, 2022). However, carbon tax does not penalize inefficient processes directly even if it is related. This presents a challenge, particularly in regions where renewable resources are scarce. In such contexts, the imperative to consume resources efficiently remains paramount, even if they are non-emitting. Therefore, while carbon taxes offer a pathway towards environmental sustainability, a comprehensive approach that addresses both efficiency and emissions considerations is imperative for effective environmental policies. A tax that is based on exergy could be an interesting alternative.

1.1. Exergy Taxes

In every process, the amount of exergy output is always lesser than the exergy input. The difference in exergy between the input and output is the result of two sinks, which are illustrated in Figure 1: exergy wasted to the environment and exergy destroyed due to inefficient process and unavoidable irreversibilities. The combination of the two will be referred to as exergy loss in the following sections. The exergy wasted refers to the exergy released to the environment due to mechanical, thermal, and/or chemical disequilibrium with the reference environment (e.g. flue gases in combustion) (Ao et al., 2008). Whereas, exergy destruction refers to the loss of the working potential of natural resources and where irreversibility occurs. This part of exergy loss has, by definition, no environmental effects (e.g. exergy destruction by heat transfer between two bodies at different temperatures) (Gong and Wall, 1997).

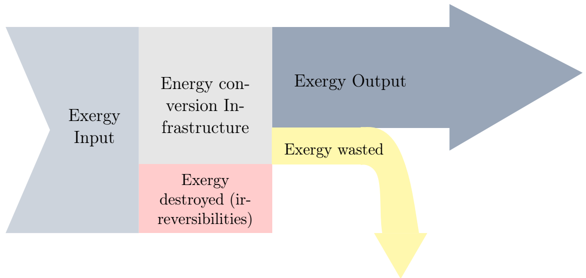


Figure 1: Exergy flow through a specific infrastructure. Exergy losses include exergy wasted to the environment and exergy destruction due to inefficiencies.

Exergy losses are a relevant way among others to assess the depletion of natural resources. An exergy tax can help minimize the use of natural resources. This has been discussed in research studies such as Ayres (2003) and Rosen (2004). Taxing exergy losses has then the potential to reduce greenhouse gas emissions and resource use.

Wall (1993) initially proposed in 1993 the introduction of an exergy tax system as an alternative to the VAT, aiming to establish a more sustainable tax framework. Over the past three decades, only a select few researchers have endeavored to implement exergy taxes within localized systems. For instance, Gong and Wall (1997) proposed an exergy tax scheme targeting non-renewable inputs and wasted exergy released into the environment. He concluded that utilizing exergy as the basis for taxation offers several advantages. Firstly, exergy can be calculated using readily available physical data for the flow and environmental conditions, potentially standardized through international agreements. Secondly, exergy is intricately linked to the utility of extracted resources and their physical (environmental) value, representing the "cost" of resource production from the ambient environment. Moreover, exergy serves as a measure of the physical value of environmental stress induced by exergy waste when it is discharged into the environment. Finally, exergy consistently maintains a positive value, as it is referenced against the natural (ambient) environment, offering a robust framework for taxation. However, Gong and Wall did not quantify the benefits of the exergy tax.
Santarelli (2004) expanded upon this by investigating the impact of a carbon exergy tax compared to conventional carbon taxation. This study focused on cogeneration plants and demonstrated that the exergy-based tax shifts the minimum cost design point to the plants' most efficient operating conditions, thereby promoting environmentally friendlier operation. In contrast, conventional carbon taxation failed to incentivize optimal efficiency and pollutant reduction in plant operation. While the carbon tax merely translated operation costs to higher values, the minimum cost design condition remained unchanged. This case study aimed to show that an exergy system could optimize the operation of a technology. He did not study the choice between different technologies.

1.2. Contribution of this work

Implementing an exergy tax at the scale of a country represents a novel and potentially instructive endeavor, yet one that has not been explored. The main objective of this thesis is to investigate the feasibility of introducing an exergy tax in Belgium and evaluate its efficiency in mitigating greenhouse gas emissions and curbing primary exergy consumption. By conducting this study, the aim is to contribute to the understanding of how such a system could evolve and its potential impact on sustainability within the Belgian context.

2. Methodology and Case Study

Previous studies showed how an exergy tax could be an interesting way of mitigating current challenges. The model chosen to analyze its effectiveness is EnergyScope (Limpens et al., 2019).

2.1. Research approach

According to Eurostat, total energy-related tax revenues amounted to around 8.5 billion euros in Belgium in 2022. Including the cost of carbon, which is gradually being excised in Belgium, total tax revenue for 2030 is expected to be 10 billion euros for the energy sector. This substantial revenue stream offers a promising opportunity to develop and implement tax policies that effectively promote sustainability in various sectors.

This study evaluates different tax systems in Belgium to identify the most suitable option for generating revenue, given the taxation target of €10 billion. This is done using ExergyScope, an adaptation of EnergyScope. This model was selected for its ability to optimize system design based on cost, providing a practical tool to assess the effectiveness of various tax schemes in shaping system evolution while minimizing costs under taxation.

This work analyzes taxes targeting exergy loss and carbon emissions. Through this comparative analysis, the study seeks to offer valuable insights into the most effective taxation strategy for attaining desired environmental and economic goals.

The various case studies are examined using different key performance indicators to evaluate their effectiveness. Each scenario is analyzed based on its emissions, cost, and exergy loss, relative to a baseline without any tax. Minimizing costs is paramount to proposing a viable system without significantly increasing tax burdens. Moreover, maintaining low levels of emissions and exergy loss is critical for establishing a sustainable system that aligns with the goals of the Paris Agreement and optimizes primary exergy utilization.

2.2. Case study

The case study proposes an analysis of the exergy tax performed using projected data from 2035. This forward-looking analysis assesses how the implementation of an exergy tax could impact the future trajectory of the Belgian energy system, providing valuable insights into potential policy interventions and their implications for sustainability and economic efficiency.

This is modeled using ExergyScope, which can be constrained with an upper bound value for emissions. However, in this study, emissions are not constrained to analyze how the system evolves without such limitations. This enables the reduction of emissions to be identified in terms of the different taxation systems, without constraining them.
The data set used for 2035 uses data proposed for EnergyScope (Limpens et al., 2019) and modified in order to handle exergy flows.

2.3. Modification of EnergyScope into ExergyScope

EnergyScope is an open-source model developed by the UCLouvain and EPFL. The EnergyScope version used for this work is EnergyScope TD (available on Github). It is a powerful linear optimization tool designed to model energy systems, from primary sources to end-use demand. Its optimization process focuses on minimizing either system cost or emissions through iterative adjustments of two key variables: technology capacities and hourly production levels.

EnergyScope TD optimizes system design and operation to meet hourly demand, based on typical day formulations, reducing computational complexity while allowing for the representation of energy storage across various time scales. The calculation of typical days depends on the time series relating to demand, and on the time series relating to variable renewable generation. For renewable generation, the relative importance of the different time series is weighted by the maximal installed capacity of the associated technologies. Moreover, the model incorporates constraints to uphold emissions limits and ensure hourly energy carrier balance.

To adapt EnergyScope into ExergyScope (available on Github) and transform each energy quantity[1] E_i into an exergy quantity X_i, the ratio between the exergy and the energy content of each energy carrier was used. This ratio is referred to as the exergy factor $e_{2x,\,i}$ (see Table 1).

Energy Carrier	$e_{2x,\,i}$	**References**
Methane	1.04	Martin and Wauters
Oil	1.06	Martin and Wauters
Hydrogen	0.98	Martin and Wauters
Biomass	1.11	Felício et al.
Methanol	0.98	Al-Breiki and Bicer
Ammonia	1.2	Al-Breiki and Bicer
Others	1	

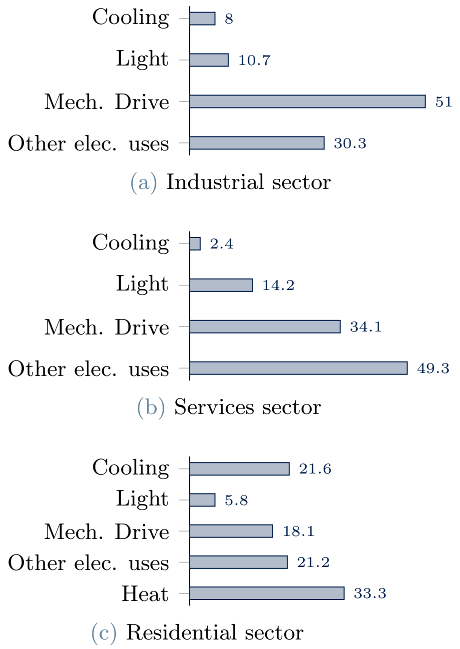
Table 1: Energy and Exergy Content of the different energy carriers used in this work.

Furthermore, the demand formulation was adapted to include only useful categories in ExergyScope. Compared to EnergyScope, ExergyScope divides the electricity demand into mechanical drive, heat, cold, light, and other electric uses. This categorization was performed using the distribution shares proposed by Serrenho et al. (2014) and adapted to the Belgian context. These shares are visually represented in Figure 2.
Moreover, in order to account for the tax analysis, a term was incorporated into the cost function. As previously mentioned, two different taxes will be studied: one concerning exergy loss and one concerning emissions.
In the cost function, these two terms are added, each associated with a coefficient representing the price of the tax in €/kWh or in €/kgCO_2. Subsequently, two different parameters are added to the model: an exergy loss fee (exergy price) and a carbon fee (CO_2 price).The cost in ExergyScope is now defined as :

$$\begin{aligned} C_{\text{tot}} = \ & \text{Total Investment Cost} \\ & + \text{Total Operation Cost} \\ & + \text{Exergy price} \cdot X_{destr.,tot} \\ & + \text{CO}_2 \text{ price} \cdot \text{GWP}_{\text{tot}} \end{aligned} \tag{1}$$

With $X_{destr.,tot}$, the total exergy loss in the system and GWP_{tot} the greenhouse gas emisisons of the system.

[1] The convention used for the energy factor is to take the lower heating value.



(a) Industrial sector

(b) Services sector

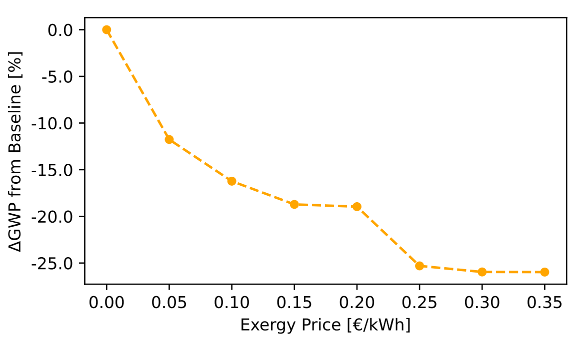
(c) Residential sector

Figure 2: Electricity repartition into useful demand for each sector

3. Results and discussions

3.1. Exergy Loss Tax

To assess the impact of a tax on exergy losses, the associated exergy price was varied between 0 and 0.35 €/kWh to understand the performance such a tax can achieve. However, the tax contribution shows that beyond an exergy price of 0.05 €/kWh, the amount of tax collected is above the current amount of tax collected (€10 billion). For a tax collection of €10 billion, exergy efficiency increases by 11%, and emissions fall by 12% compared to the baseline situation (without tax).



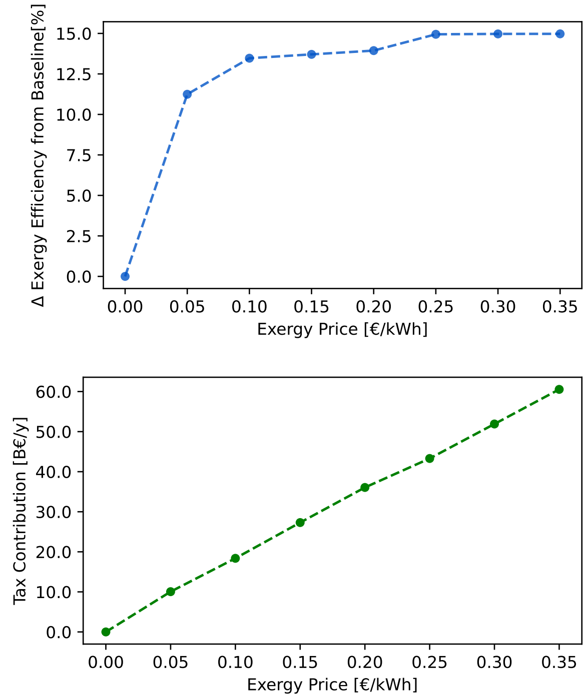


Figure 3: The variation in exergy loss shows an increase in the amount of tax levied to reduce emissions of up to 25% and a maximum increase in exergy efficiency of 15%.

As illustrated in Figure 3, the amount of money collected by the tax system increases proportionally with the price of exergy loss. As mentioned above, exergy loss is inherent in the transformation of one form of energy into another. The tax does not aim to eliminate this loss, only to reduce it. The fact that this tax can be collected even if the system tends towards greater efficiency is an advantage because it is an alternative to the VAT system. The state can recover money from any energy transformation activity with an exergy loss tax system.

3.2. Exergy Loss Tax combined with a Carbon Tax

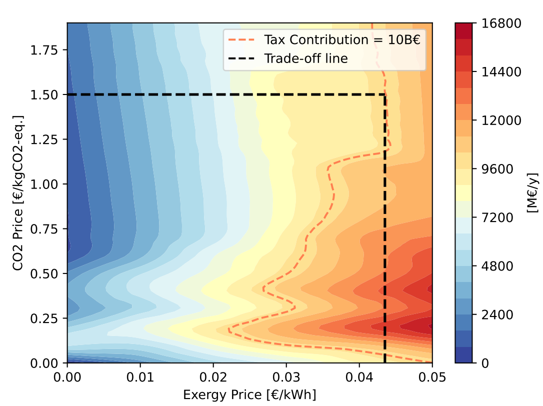


Figure 4: Emissions and exergy loss tax contribution

To ensure that emissions are more reduced in the future, it is also possible to consider a tax system targeting both emissions and exergy loss.
Figure 4 shows the approximated combinations of carbon and exergy loss prices that result in a sufficient tax levy (orange dashed curve). Plotted in Figure 5, this curve shows all the valid combinations and their impact on emissions and exergy efficiency. To increase exergy efficiency and radically reduce emissions, an arbitrary compromise is to take a CO_2 price of 1.5 €/kgCO_2-eq. and an exergy loss price of 0.0435 €/kWh.
This choice results in an exergy efficiency increase of 9 % and an emissions reduction of almost 100%.

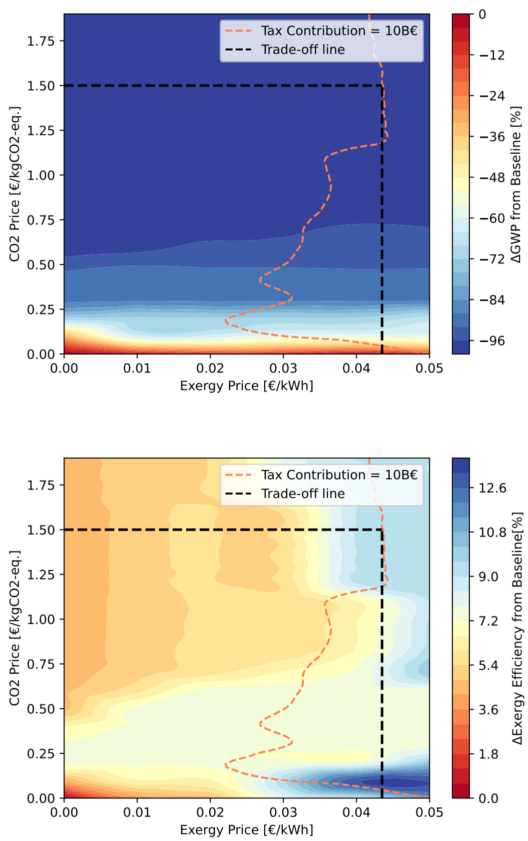


Figure 5: Exergy loss and CO_2 price variations. In this work the optimum chosen to levy the right tax amount is with an exergy price of 0.045€/kWh and a carbon price of 1.5 €/kgCO_2.

3.3. Comparing Exergy-Based Taxes to Carbon Tax

Although two exergy-based tax systems have been analyzed to propose their potential implementation in Belgium, the effectiveness of these measures compared to a carbon tax merits further study. The simplicity of implementing a carbon tax, already envisaged in Belgium (FPS Health and Environment, 2023), raises questions about the effectiveness of more complex systems.

Figure 6 illustrates the impact of a carbon tax alone, showcasing variations in CO_2 prices and their influence on emissions and exergy efficiency. As anticipated, the tax significantly reduces emissions; however, it falls short of achieving a similar level of exergy efficiency as those obtained with exergy-based tax systems. In this study, a CO_2 price of 0.7€/kgCO_2 is selected as it corresponds to the minimum price that optimizes the tax's performance, resulting in a remarkable 99.46% reduction in emissions compared to a tax-free scenario.

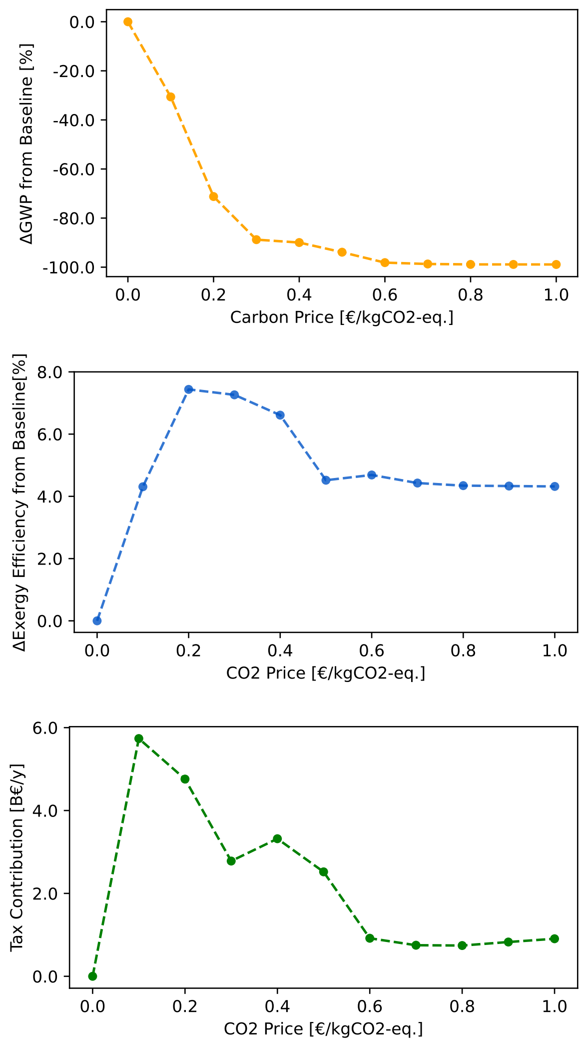


Figure 6: Variations on the carbon tax show that it is a tax system capable of reducing emissions by almost 100%, but only with a 4% increase in exergy efficiency and without the right amount of tax levied.
Table 2 presents a comparative analysis of various tax systems, evaluating the effectiveness of an exergy-based tax against a carbon tax. Concerning the defined parameters of a sustainable tax system in this study - one that generates sufficient revenue (€10 billion), enhances exergy efficiency, and maintains

low emissions - it becomes evident that a standalone carbon tax does not fully meet these criteria. Prasad (2022) showed that if carbon taxes are substituted for other taxes, then the tax base of the state becomes dependent on the revenue from carbon taxes. If that revenue declines—as it surely must, given the rapid development of alternative energy and energy efficiency technologies, which will make it easier for firms and individuals to reduce carbon emissions and therefore no longer need to pay the tax—then the tax base of the state declines. Consequently, it necessitates integration with another tax scheme to achieve desired taxation levels. Presently, Belgium's approach involves combining the carbon tax with Value Added Tax (VAT), a strategy aimed at both revenue generation and emission reduction (FPS Health and Environment, 2023).

However, it is possible to attain the dual objectives of robust tax revenue and minimal emissions by augmenting considerably exergy efficiency (see Table 2) through a combination of a carbon tax with an exergy loss tax. However, it should be noted that the latter option leads to an energy system requiring higher investment and operating costs (+35% compared to the baseline).

Exergy loss tax alone is a good start to reduce emissions but it necessitates improvements to reach a more ambitious reduction of emissions in the coming decades. The main advantage of an exergy loss tax is the reduction in primary energy use. As shown in Table 2, while the carbon tax only reduces by 4% energy supplied to the system, all the exergy-based taxes reduce by at least 21% the energy resource.

4. Discussion on Tax Collection

The tax systems were designed to retribute €10 billion. However, this amount is reached only when optimality occurs. That means that the state will collect a higher amount of taxes before the system reaches its optimal cost (incl. investment, operations, and taxes). For example, the exergy tax alone has been tested in the year 2015 which is constrained to represent the Belgian system at that time. A tax collection of 20B€ is estimated with an exergy loss price of 0.05€/kWh. That means that the state collects at the beginning double the amount as is the case today.

Caetano and Marques (2023) has shown how, in a society where profit remains the driving force behind business decisions, industries could move to countries with lower levels of taxation. However, emissions need to be reduced on a global scale. As Jäger (2023) explains, it is important to keep energy-intensive industries in Europe and help them decarbonize, rather than taxing them to the point of driving them away. This could be achieved through the tax revenues collected, as proposed by Prasad (2022).

Gradual implementation of a tax system could prevent investment and operating costs from rising drastically all at once. Then current exergy destruction and emissions levels can be used to define costs that allow a tax collection of 10 billion euros with the current Belgian energy system. Then the proposed tax system targeting emissions and exergy loss can be fully deployed in 2050 in order to reach net zero emissions by then. To analyze the impact of such a gradual implementation, the version of EnergyScope transformed into ExergyScope is no longer adequate because it does not allow to take into account the evolution of the model. It is instead a snapshot model. Then, it would be better to use the version of EnergyScope that allows pathways. The latter was devel-

	Carbon Tax	**Exergy loss Tax**	**Combined Carbon and Exergy loss Tax**
CO_2 price [€/kgCO_2]	1	0	1.5
Exergy price [€/kWh]	0.0	5e-2	4.4e-2
NR price [€/kWh]	0.0	0.0	0.0
Tax revenues [B€/y]	0.91	9.96	10.20
Difference from Baseline [%]			
ΔTotal cost (investment and operation)	30.47	5.74	35.14
ΔEmissions	-98.90	-11.76	-99.46
ΔExergy Efficiency	4.32	11.36	9.02
ΔPrimary Energy	-4.01	-25.54	-21.50

Table 2: Comparative Analysis of the different tax systems

oped by Limpens et al. (2024) but requires its adaptation into ExergyScope.

5. Limitations of this work

This work provides an interesting tax framework but some aspects are not well covered and require further studies.

First of all, this work needs to be extended to a larger scale to understand the interactions between countries. Thiran et al.'s development of EnergyScope Multicell could be adapted to handle exergy flows. This could be done in the same way as for ExergyScope TD (available on Github). This would make it possible to implement different tax systems and analyze their expected effects beyond Belgium.

Moreover, this study did not consider different demand scenarios. The implementation of exergy-based tax systems could exert pressure on the economy and potentially lead to the closure of high-emitting industries. It is crucial to account for these factors to propose a viable tax system. Furthermore, for the proposed system to be viable, various strategies need to support it. For example, to prevent industries from moving to less-taxed countries, a strategy to counter this effect must be put in place. This can be achieved by introducing a tax at the borders of a region, as is the case with the Border Carbon Adjustment Mechanism (BCAM). This mechanism was introduced by the EU to set a fair price on the carbon emitted during the production of carbon-intensive goods entering the EU, in order to encourage cleaner industrial production in third countries while avoiding the relocation of industries (CBAM).

Achieving a net-zero energy system is one of the key milestones towards a more sustainable society. However, it must be strategically planned to ensure the economic viability of Belgian society. The United Nations has adopted seventeen Sustainable Development Goals (SDGs) that encompass all facets of a more sustainable society. A more precise method for assessing the benefits and drawbacks of an exergy-based tax concerning different SDGs and scenarios is necessary.

6. Conclusion

Without increasing the total tax burden, exergy-based taxes can encourage the reduction of products that have a significant environmental impact (Szargut et al., 1988). In this context, a strong environmental impact was defined by the combined high use of primary energy and emissions.
It has been demonstrated that exergy-based taxes can effectively reduce emissions and primary energy use. The most efficient tax targets both emissions and exergy losses, proving to be more effective than a tax targeting solely emissions.

This initial analysis is a crucial first step in assessing their benefits. However, implementing this taxation system would significantly increase system costs (both installation and operations), potentially leading to undesirable economic consequences such as the closure of industries. These potential outcomes must be thoroughly examined and weighed against the benefits. Further research is needed to analyze in depth the impact of exergy-based taxes, particularly their phased implementation.

A significant drawback of exergy-based taxes is their reliance on the concept of exergy, which is not widely understood by the general population and requires knowledge of thermodynamics. Despite this challenge, the analysis presented here has been limited to the energy sector. It would be valuable to extend this analysis to the entire economy. Exergy-based taxes have the potential to reduce resource depletion comprehensively (Szargut, 2002). If proven effective, policymakers would have a new tool to ensure the uptake of the transition to sustainability.

While taxes can initiate the transition, policymakers need to encourage broader changes. Indeed, the tax proposed in this work is designed to maintain or increase current demand levels, but it is also essential to consider the concept of sobriety. As Balzani (2019) pointed out, the least polluting energy is the energy we do not consume.

In conclusion, exergy-based taxes present a promising avenue for promoting sustainability and reducing environmental impact. However, their implementation requires careful consideration of economic and societal impacts, as well as broader public education on exergy and its importance.

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