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Identifying Tipping Points in the Belgian Energy Transition: A Parametric Analysis with EnergyScope TD and Prospective Life Cycle Assessment of Renewable Fuels

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Academic year 2024–2025
Master [120] in Electro-mechanical Engineering

Acknowledgments

I would like to express my sincere gratitude to Nicolas G. for his valuable guidance and insightful advice throughout this work.

I also wish to thank my parents for their patience and continuous encouragement.

A special acknowledgment goes to the welcoming,if occasionally productive, environment of the basement level (-1) of the Stevin building. Writing my Master's thesis while striking a balance between hard work and funny *little* talk was a real pleasure.

Finally, the writing of this Master's thesis was made significantly more bearable thanks to the person who endured my complaints, witnessed my moments of joy, and most importantly, withstood my long, dramatic monologues. Yes, thank you, Emile.

I would also like to acknowledge the use of ChatGPT for the translation and reformulation of numerous passages, which greatly contributed to making this thesis more readable and stylistically consistent.

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Chapter 1

Introduction

1.1 Climate context

According to [13], every additional 1000 $GtCO_2$ of cumulative anthropogenic emissions is estimated to raise the global mean surface temperature by approximately 0.45 °C, with a likely range between 0.27 and 0.63 °C.

Recent assessments of the remaining carbon budget, calculated from the beginning of 2020, indicate that only about 500 $GtCO_2$ can still be emitted to retain a 50% chance of limiting warming to 1.5 °C, while approximately 1150 $GtCO_2$ corresponds to a 67% probability of stabilising warming at 2 °C.

All global scenarios consistent with limiting warming to 1.5 °C (with a probability greater than 50%), whether with no or only limited overshoot, as well as those targeting 2 °C (with a probability greater than 67%), converge on the same conclusion: greenhouse gas emissions must decline rapidly, deeply, and in most cases immediately, across all sectors. In these pathways, global net CO_2 emissions reach neutrality by the early 2050s for the 1.5 °C target, and by the early 2070s for the 2 °C target.

Confronted with this climate emergency, countries are compelled to radically rethink their energy strategies. Long-term planning now requires identifying which resources and technologies will underpin tomorrow's energy systems.

To inform this process, a wide range of energy system models have been developed. These models differ in their underlying concepts and methodological choices, giving rise to broad families of approaches that aim to analyse, design, and optimise the energy transitions required for a sustainable future.

1.2 Energy models

1.2.1 What are energy models used for?

In a context where energy transition is a global strategic issue, energy models are essential tools for supporting long-term decision-making. They enable the future evolution of a complex energy system subject to multiple constraints, whether economic, technological, environmental or geopolitical, to be simulated in a coherent and integrated manner. These forward-looking tools are used to anticipate the effects of public policies, estimate investment needs, evaluate the performance of emerging technologies and build robust transition trajectories. For decision-makers, they provide a rational basis for multi-criteria analysis to arbitrate between different options, taking into account objectives such as security of supply, economic sustainability, or carbon neutrality. They are therefore essential for developing realistic energy roadmaps tailored to local specificities.

1.2.2 What is an energy model?

Conceptually, an energy model is a mathematical representation of an energy system, incorporating all of its components: energy production, conversion, transport, storage and consumption. It is based on a set of equilibrium equations, physical and economic constraints, and a detailed database describing the technical and economic characteristics of different technologies and energy carriers. Among the most comprehensive models, so-called *whole-energy system* models seek to simultaneously model several sectors (electricity, heat, mobility, industry) and carriers (electricity, gas, synthetic fuels) in order to capture intersectoral interactions and synergies. These models generally formulate an optimisation problem (linear or mixed) aimed at determining the most efficient system configuration according to a given objective (total cost, emissions, EROI, etc.), while respecting the constraints imposed.

1.2.3 How do they work?

Energy modelling is based on two main analytical paradigms:

- **Top-down approach**: macroeconomic, this approach models the energy system as a subset of a global economic equilibrium model. It is suitable for analysing the impact of large-scale economic policies.
- **Bottom-up approach**: this technological approach details the available technologies and their performance. It allows for detailed modelling of transition options and is preferred for the technical analysis of energy scenarios.

Finally, the level of temporal detail (hourly, daily, seasonal) strongly influences the model's ability to integrate the variability of renewable resources and storage needs.

1.2.4 Classification of energy models

The classification of energy models depends on several dimensions:

Time horizon

- **Operational models**: Short-term models are used for operational tasks such as unit commitment and operation adequacy. They aim to ensure the optimal functioning of the existing system at a given moment or over a limited period.
- **Design**: Long-term models are part of an energy strategy. They are used for expansion planning, with a time horizon generally exceeding one year. When the horizon becomes sufficiently long, we refer to **system planning**: it becomes possible to make fundamental changes to the overall architecture of the energy system.
- **Scenario analysis**: finally, if the time horizon is sufficiently distant to allow us to disregard the existing system, models can fully optimise the design of a future energy system from scratch. This approach makes it possible to construct transition scenarios towards a target system consistent with long-term objectives.

Simulation versus optimization

- Simulation models are primarily descriptive in nature: they aim to reproduce as faithfully as possible the behaviour of an energy system under a predefined set of assumptions. Rather than seeking a unique optimal solution, they explore how the system responds to changes in demand, supply, technology, or policy conditions. This makes them particularly suitable for short- to medium-term analyses, where the emphasis lies on understanding system dynamics and interactions rather than on prescribing an ideal configuration. By allowing analysts to test different scenarios and assumptions, simulation models provide valuable insights into the operational performance of the energy system under diverse conditions.
- Optimisation models, by contrast, are prescriptive tools designed to identify the best configuration of the energy system within a well-defined decision space. They rely on formal mathematical formulations in which decision variables

are adjusted by algorithms to minimise the costs, maximise the efficiency, or achieve other policy-driven objectives, all while respecting technical and environmental constraints. Such models are especially relevant for long-term planning, as they allow decision makers to assess which investment pathways, technology choices, or resource allocations are most cost-effective or most compatible with climate and energy targets. Well-known frameworks such as MARKAL/TIMES fall into this category.

1.2.5 What criteria should be used to choose a relevant model?

In addition to typology, several criteria should guide the selection of a model for energy planning:

- **Multisectoral approach**: a relevant model must cover all energy sectors: electricity, heat, mobility and non energetic demand, and integrate their interactions. The transition to a fossil fuel-free system requires a systemic approach in which intersectoral linkages (heating electrification, electric vehicles, cogeneration, etc.) play a decisive role. A single-sector model would only provide a partial understanding of systemic dynamics.

- **Open-source availability**: making the model, including its source code, publicly available is essential for scientific transparency. It allows for the reproducibility of results, methodological verification by third parties, and the possibility of adaptations to the specific needs of new studies.

- **Temporal resolution**: in a context of high penetration of intermittent renewable energies (solar and wind) and massive use of storage, hourly resolution is often essential. It allows daily and seasonal fluctuations to be accurately captured, thereby optimising both capacity investments and operational management of the system.

- **Computing time**: Optimisation models with hourly resolution over all 8,760 hours of the year are particularly demanding in terms of computing resources. To remain practical, particularly in the context of sensitivity or uncertainty analyses, it is essential to favour models that offer a reasonable compromise between granularity and computation time, ideally in the order of a few minutes per simulation or less.

1.3 Contribution of this thesis

1.3.1 EnergyScope Typical Days

The EnergyScope model constitutes a comprehensive optimisation framework designed to co-optimise the structure and operation of all major energy sectors. These sectors encompass electricity, heat, mobility, and non-energy demands, treated with uniform granularity and systemic integration.

Originally developed at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland in 2011, EnergyScope has since evolved through continued collaboration between EPFL and UCLouvain (Belgium). For an exhaustive presentation of the model's construction and methodological assumptions, the reader is referred to the doctoral dissertations of Gauthier Limpens [**?**] and Stefano Moret [30].

The present work employs EnergyScope-TD (Typical Days), a variant of the model tailored for strategic energy planning, in Belgium. This formulation adopts a *snapshot* approach, optimising the energy system for a representative year instead of optimizing its continuous temporal evolution. (Energyscope Pathway)

- **Optimisation-based framework:** nergyScope is not a cost minimising optimisation model subject to physical, technical, and policy constraints. It identifies cost-effective system configurations that comply with projected energy service demands and environmental objectives.
- **Snapshot formulation:** The model solves for a single representative year. In contrast to dynamic models, EnergyScope does not explicitly model temporal trajectories, although such long-term dynamics can be approximated through its dedicated version, EnergyScope Pathway.
- **Deterministic linear programming:** The model is formulated as a deterministic, continuous, linear optimisation problem. Enabling the derivation of a unique global optimum through standard linear programming solvers.
- **Hourly resolution on representative days:** Temporal resolution is achieved through the use of *typical days*, selected via clustering techniques to capture seasonal and diurnal variability. Each day is resolved on an hourly basis, offering a balance between model tractability and temporal fidelity.
- **Multi-sector integration:** EnergyScope concurrently optimises energy flows across electricity, heating, mobility, and storage sectors, enabling the analysis of cross-sectoral interactions and synergies.
- **Open-source accessibility:** The model is fully open-source and extensively documented, see [5]. It is publicly available via GitHub.

A more detailed description of the EnergyScope-TD model, including its structural assumptions, mathematical formulation, and specific relevance to the objectives of this master's thesis, is provided in the dedicated chapter later in this document.

Emissions in EnergyScope

The EnergyScope model accounts for two types of greenhouse gas emissions: the operational emissions (GWP_{op}), which are linked to the use of energy resources, and the construction emissions ($GWP_{construct}$), which are associated with the construction of technologies.

Operational emissions are model input parameters defined for each resource available to the system. These values encompass the emissions from resource extraction, transportation, and eventual combustion. A more detailed explanation of these processes is provided in Chapter 2.

In the current implementation of EnergyScope, only the emissions related to resource usage (GWP_{op}) are taken into account.

A key assumption in the existing version of the model is that renewable fuels have negligible operational emissions. This implies either that their emissions are assumed to be orders of magnitude lower than those of fossil fuels, or that their influence on the system-wide optimisation is considered insignificant.

However, two main limitations emerge from this assumption:

- Conventional life cycle assessment (LCA) methods are inadequate for estimating the operational emissions of renewable fuels projected for 2050.It is essential to account for the evolution of the global energy system that underpins the production of renewable fuels.
- At what threshold can the operational emissions of a resource be considered negligible in terms of their impact on the model's energy system optimum? There is no a priori criterion to determine which levels of operational emissions can be legitimately considered negligible.

1.4 Research questions

This master's thesis aimed to address two key limitations of the EnergyScope model in its current formulation:

- The implementation of a more realistic estimation of the life cycle carbon impact of renewable fuels.

- The integration of Shared Socioeconomic Pathways (SSPs) to refine long-term parameter assumptions, with a focus on the year 2050.

Through these two modelling enhancements, this work sought to answer the following questions:

- How does the integration of life cycle carbon impacts of renewable fuels alter the model energy system optimum for Belgium by 2050 ?
- What would constitute a more accurate estimation of the carbon impact associated with renewable fuels imported into Belgium in 2050?

1.4.1 Outlines of this thesis

- **Energy system model: EnergyScope**: presentation of the model structure and mathematical formulation, with a particular focus on the operational emission parameter investigated in this work.
- **Case study : The Belgian energy system in 2050**: Presentation of demand profiles, available resources, and technologies. Introduction of the 2050 reference energy scenario, based on the current assumptions implemented in EnergyScope.
- **Tipping points in the Belgian energy scenario**: Identification and analysis of tipping points between resources and major energy conversion technologies in the model, through parametric variation of the operational emissions of renewable fuels, with a focus on defining thresholds between competing energy pathways.
- **Prospective Life Cycle Assessment of renewable fuel supply chains in Europe (2050 Horizon)**: Justification and explanation of choosing pLCA over traditional LCA. Presentation of renewable fuel production pathways. Methodologies and limitations of the prospective LCAs conducted.
- **Conclusion**: Summary of conclusions and key findings

Chapter 2

Energy system model : Energyscope

2.1 Energy system model

2.1.1 EnergyScope TD

The EnergyScope TD model is a fully open-source, whole-energy system optimisation framework. It is designed to simultaneously consider all key energy sectors: electricity, heat, transport, and non-energy demands, within an integrated perspective. In this thesis, the variant employed is the snapshot version, which evaluates cost-optimal system configurations for a single target year, without explicitly modelling the transitional pathway from the current system to that future state.

2.1.2 Overview of the EnergyScope TD Framework

The EnergyScope Typical Days (TD) framework is structured as a two-step methodology, designed to decouple temporal representativity from system optimisation.

- **Step 1 – Selection of Typical Days:** This preliminary step consists in extracting a limited set of representative days, referred to as typical days, from high-resolution temporal datasets such as meteorological or demand profiles. The objective is to preserve the temporal variability of inputs (e.g., solar irradiation, wind profiles, load curves) while reducing computational burden. This step is performed only once for a given energy system configuration and associated weather year.
- **Step 2 – Energy System Optimisation:** Based on the selected typical days, a linear optimisation model is used to design the optimal energy system

configuration under specific scenarios and constraints. This step can be repeated multiple times to assess different transition pathways, policy options, or technological assumptions.

The independence of these two steps allows for an efficient modelling workflow. The typical days extraction is invariant to scenario-specific assumptions and thus serves as a reusable input for diverse optimisation runs. This modularity is particularly relevant for long-term scenario analysis and sensitivity assessments within the energy transition context.

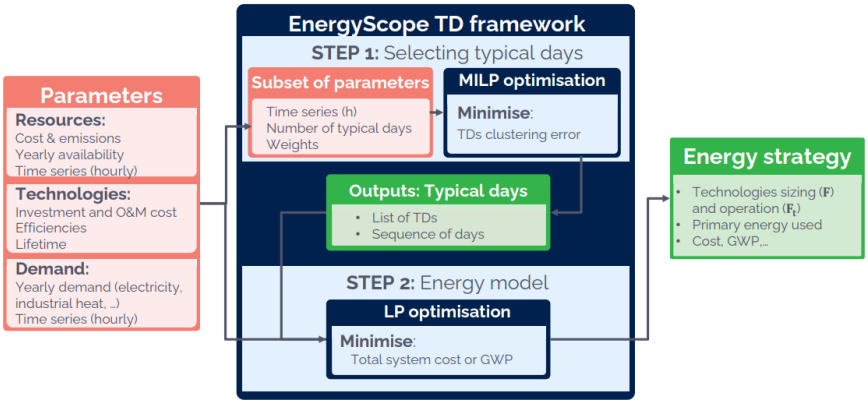


Figure 2.1: Overview of the EnergyScope TD framework, from [25]

Linear programming formulation

The energy system model is formulated as a linear programming (LP) problem, a widely used optimisation framework for system design under constraints. The LP formulation is composed of five fundamental components:

- **Parameters:** These are fixed and exogenous inputs to the model, representing known quantities such as demand time series, resource availabilities, or technical and economic characteristics of technologies. Parameters also define upper and lower bounds for the decision variables.
- **Variables:** These represent the unknowns to be determined by the model. They include, for instance, the installed capacity of a given technology, the energy flows between system components, or the operation of storage units. Each variable is constrained by parameter-defined bounds, which may reflect physical or policy limitations.

- **Decision Variables:** A subset of the variables that are directly optimised by the model. These can be continuous (e.g., installed capacity in MW), and may or may not be subject to bounding constraints. The values of the other dependent variables are determined based on the structure of the model and the decision variable values. For example, the investment cost of wind turbines is a dependent variable, as it is directly determined by the number of wind turbines, which is itself an independent decision variable.
- **Constraints:** They ensure consistency with the laws of conservation (e.g., energy balance), operational feasibility (e.g., capacity limits), and policy targets (e.g., emission reductions).
- **Objective Function:** This is a scalar function of the decision variables that the model seeks to optimise. In most energy system applications, the objective is to minimise the total annualised cost of the system.

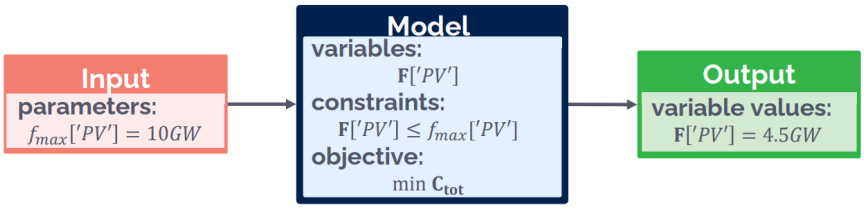


Figure 2.2: The *EnergyScope TD* model optimises the installed capacities of all considered technologies,denoted by the decision variable F in the model's formulation and visual representations.

2.1.3 Conceptual modelling framework

The primary objective of the model is to ensure the satisfaction of energy balance constraints, implying that demand is an exogenous input and must be met entirely by the supply system.

Expression of Demand. The modelling framework focuses on the end-use demand (EUD), which quantifies the energy required to fulfil specific final needs. In contrast, final energy consumption (FEC) represents the quantity of input energy necessary for a technology to satisfy this demand. For instance, the electricity consumed by a heat pump constitutes the FEC, while the thermal energy delivered to the user corresponds to the EUD. According to the European Commission, FEC is defined as "the energy which reaches the final consumer's door", i.e., the input energy required to provide energy services.

Model Input. The primary input of the model is the EUD expressed in terms of energy services, structured across four distinct sectors: electricity, heating, mobility, and non-energy demand.

Definition of Layers. The model introduces the concept of layers, which refer to all system components whose balance must be ensured at each time step. These include resource flows and end-use types (EUTs), see Figure 2.4 for the representation of the electricity layer. Layers are interconnected through technologies and facilitate the flexible integration of multiple energy carriers into the same technological processes, see Figure 2.3. For example, renewable methane is allocated to the gas layer and can be accessed by any technology that utilises this layer.

Technology Classification. The model distinguishes between three categories of technologies: end-use technologies, storage technologies, and infrastructure technologies. End-use technologies are responsible for converting energy from one layer to a designated end-use layer. For example, a combined heat and power (CHP) unit transforms natural gas into both heat and electricity. Storage technologies, by contrast, operate within the same layer, enabling temporal decoupling between supply and demand such as thermal storage (TS) for heat or pumped hydro storage (PHS) for electricity. Infrastructure technologies comprise all remaining conversion and transmission processes, including energy networks, like the electrical grid and district heating networks (DHNs), as well as inter-layer conversion technologies. Notable examples include the gasification of biomass to produce methane, or the reforming of methane to generate hydrogen.

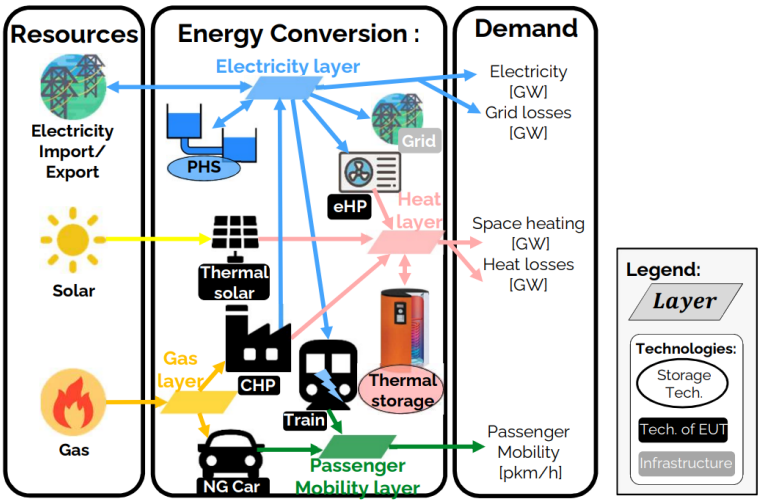


Figure 2.3: Conceptual illustration of an energy system with 3 resources, 8 technologies (2 storages (in colored oval) and 1 infrastructure (grey rectangle)) and 3 end-use demands. Illustration from [25]

The layers encompass all end-use types (EUTs): electricity, low-temperature heat, high-temperature heat, passenger mobility, and freight mobility.

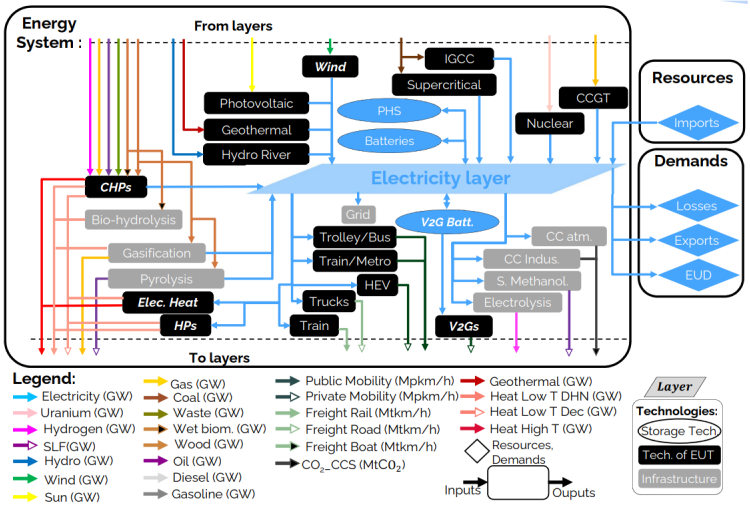


Figure 2.4: Representation of the Electricity layer with all the technologies implemented in EnergyScope Typical Days. Illustration from [25]

2.1.4 Linear Programming Model Formulation

End-Use Demand. The model expresses demand through the end-use demand (EUD) metric. This formulation allows the supply side to focus on the selection of appropriate energy conversion technologies. Depending on the chosen technology, the same EUD may be satisfied with different levels of final energy consumption (FEC), reflecting variations in conversion efficiencies.

Cost, Emissions and Objective Function. The objective function of the EnergyScope TD model aims to minimise the total annualised cost of the energy system, denoted as $\mathbf{C}_{\text{tot}}$:

$$\min\ \mathbf{C}_{\text{tot}} = \sum_{j \in \text{TECH}} \Big(\tau_j\, \mathbf{C}_{\text{inv}}(j) + \mathbf{C}_{\text{maint}}(j) \Big) \ + \sum_{i \in \text{RES}} \mathbf{C}_{\text{op}}(i) \tag{2.1}$$

where the annuity factor $\tau(j)$ is defined as:

$$\tau(j) = \frac{i_{\text{rate}}\,(1+i_{\text{rate}})^{\text{lifetime}(j)}}{(1+i_{\text{rate}})^{\text{lifetime}(j)} - 1} \quad \forall j \in \text{TECH} \tag{2.2}$$

The investment, maintenance, and operating costs are computed respectively as:

$$\mathbf{C}_{\text{inv}}(j) = c_{\text{inv}}(j)\, F(j) \quad \forall j \in \text{TECH} \tag{2.3}$$

$$\mathbf{C}_{\text{maint}}(j) = c_{\text{maint}}(j)\, F(j) \quad \forall j \in \text{TECH} \tag{2.4}$$

$$\mathbf{C}_{\text{op}}(i) = \sum_{\substack{t \in \mathcal{T},\\ (h,td) \in T_{H,TD}(t)}} c_{\text{op}}(i)\ F_t(i,h,td)\ t_{\text{op}}(h,td) \quad \forall i \in \text{RES} \tag{2.5}$$

2.1.5 Accounting for Emissions

The environmental performance of the energy system is evaluated through its total greenhouse gas emissions, expressed in terms of global warming potential (GWP). The total annual operational emissions, denoted as GWP_{tot}, are computed as follows:

$$\text{GWP}_{\text{tot}} = \sum_{j \in \text{TECH}} \frac{\text{GWP}_{\text{constr}}(j)}{\text{lifetime}(j)} + \sum_{i \in \text{RES}} \text{GWP}_{\text{op}}(i) \tag{2.6}$$

$$\text{In this version of the model:} \quad \text{GWP}_{\text{tot}} = \sum_{i \in \text{RES}} \text{GWP}_{\text{op}}(i) \tag{2.7}$$

$$\mathrm{GWP}_{\mathrm{constr}}(j) = \mathrm{gwp}_{\mathrm{constr}}(j) \cdot F(j) \quad \forall j \in \mathrm{TECH} \tag{2.8}$$

$$\mathrm{GWP}_{\mathrm{op}}(i) = \sum_{\substack{t \in T \\ \{h,td\} \in T_{H_TD}(t)}} \mathrm{gwp}_{\mathrm{op}}(i)\ F_t(i,h,td)\ t_{\mathrm{op}}(h,td) \quad \forall i \in \mathrm{RES} \tag{2.9}$$

where $\mathrm{gwp}_{\mathrm{op}}(i)$ is the emission factor of resource i [ktCO$_2$-eq./GWh], $F_t(i,h,td)$ is the installed capacity of resource i at time t, and $t_{\mathrm{op}}(h,td)$ is the duration of operation.

In the version of the model employed in this thesis, the construction-related emissions, $\mathrm{GWP}_{\mathrm{constr}}$, are not considered in the global warming potential calculation. Consequently, Equation (2.6) is simplified to Equation (2.7), where only the operational emissions of primary energy resources are accounted for.

Although $\mathrm{GWP}_{\mathrm{constr}}$ is not considered, the EnergyScope model is designed to incorporate it when required.

To ensure environmental compliance, a global emissions constraint is introduced:

$$\mathrm{GWP}_{\mathrm{tot}} \leq \mathrm{gwp_limit} \tag{2.10}$$

This constraint enforces an upper bound on total annual operational emissions, in accordance with climate policy targets.

2.2 Parameters studied in this master thesis

$\mathrm{GWP}_{\mathrm{constr}}$ denotes the emissions associated with the construction and end-of-life phases of energy conversion technologies, allocated annually over their lifetime. Conversely, $\mathrm{GWP}_{\mathrm{op}}$ represents the direct and indirect emissions linked to resource use.

In his thesis, G. Limpens identifies three approaches to account for the $\mathrm{gwp}_{\mathrm{op}}$ of a resource:

- combustion-only emissions (direct emissions);
- life-cycle emissions including production, transport, and combustion, based on the IPCC 2013 GWP100a method(indirect + direct emissions);
- full life-cycle emissions, extending the previous method to include construction-related emissions of conversion technologies.

To ensure comparability with the European Commission and the International Energy Agency (IEA), which primarily consider GWP_{op} and neglect GWP_{constr}, this thesis adopts the second approach, as reflected in Equation (2.6). Within the EnergyScope framework, this corresponds to a cradle-to-combustion perspective, excluding construction-phase emissions of the technologies chosen by the model to consume the resources.

In the present version of the modele Energyscope, for electro-fuels and biofuels, upstream emissions are omitted(indirect emissions), and combustion is assumed carbon-neutral, as the CO_2 released is offset by biomass regrowth.

2.2.1 Direct and indirect emissions related to resources

The boundaries of gwp_{op} encompass all emissions from the extraction, transport, and combustion of resources. While combustion is generally the most emission-intensive phase for a fuel, the contributions from production and transport are not negligible. For biomass, which is considered sustainable, the combustion-phase emissions exceed the overall life-cycle emissions due to the carbon-neutrality assumption.

Table 2.1: GHG emission factors for different resources, at combustion stage and overall life-cycle, from G. Limpens thesis [25]

Resources	**Combustion** [$kgCO_2$-eq./MWh_{fuel}]	**Overall** [$kgCO_2$-eq./MWh_{fuel}]
Gasoline / Bio-Gasoline	250	345
Diesel / Bio-Diesel	270	315
Light fuel oil / synthetic liquid fuel	280	311
NG / synthetic NG	200	267
Waste[c]	150	150
Uranium	0	3.9
Coal[e]	340	401
Biomass[f]	390	11.8

Indirect emissions are highly dependent on the production pathway of a renewable fuel. For instance, an electro-fuel, for which electricity constitutes the majority of inputs, is strongly influenced by the carbon intensity of the electricity used. Its designation is therefore contingent upon the electricity source, as discussed in Section 5.4.1.

In the coming years, indirect emissions are expected to decrease as the economy progressively decarbonises, making them dependent on the background energy mix.

In the current EnergyScope implementation, indirect emissions from so-called renewable fuels are neglected, and the carbon neutrality assumption is applied.

This assumption implies that the model has access to six biofuels with zero operational impact (gwp_{op}): the renewable equivalents of gas, methanol, ammonia, diesel, ethanol, and hydrogen.

2.2.2 Scope of direct and indirect emissions

As outlined earlier, the gwp_{constr}(tech) parameter denotes the emissions from the construction phase of each technology in the model, assessed through a cradle-to-gate life-cycle perspective. Conversely, the gwp_{op}(res) parameter,also referred to as operation-related emissions, captures the total emissions associated with resources, following a cradle-to-combustion scope. This latter approach extends beyond conventional methods that focus solely on combustion (direct emissions) by also including indirect emissions from extraction, transport, and related processes.

In this study, in order to estimate an operational global warming potential (GWP_{op}) that is directly comparable with the other resources imported from the model, the emissions associated with infrastructure required for the production of the resource (e.g., the anaerobic digester used for methane production) are incorporated into the gwp_{op} calculation for renewable resources.

Chapter 3

Case study : The Belgian energy system in 2050

3.1 The Belgian energy system

A suitable case study must be sufficiently challenging, characterised by a significant distance from carbon neutrality, substantial demand across all sectors, and a limited availability of resources. The Belgian energy system meets all these criteria.

Belgium constitutes a particularly relevant case study for investigating energy system transition strategies. Its small geographical size and high population density, combined with a significant lack of domestic energy resources, result in a substantial dependence on energy imports to satisfy its primary energy demand. According to [18], the estimated deficit in endogenous resources amounts to approximately 275.6 TWh/year, corresponding to 30-40% of the national primary energy consumption. To address this gap, several strategies are considered, including the importation of renewable fuels and electricity, as well as the deployment of geothermal energy. This study identifies that a diversified combination of these solutions offers the most cost-effective path towards low-carbon emissions. While imported renewable fuels may exhibit lower greenhouse gas (GHG) emissions compared to local renewable resources such as solar and wind, the current maturity of life-cycle gwp data for renewable fuels remains insufficient to support definitive conclusions.

Renewable potentials, while diverse, are constrained by land availability, spatial planning considerations, and societal acceptance of large-scale energy infrastructure. For instance, solar photovoltaic deployment is limited by suitable roof and land surfaces, while onshore wind faces both spatial saturation and public opposition. Offshore wind, though promising, is bounded by maritime spatial planning and ecological considerations.

This chapter presents an overview of the energy resources available to Belgium in

the year 2050, as submitted to the EnergyScope model as input data. Subsequently, the reference scenario is introduced. This scenario represents the carbon neutrality pathway proposed by the model under its full set of assumptions, in particular the hypothesis of zero operational greenhouse gas emissions for renewable energy resources.

3.1.1 Resources

The energy resources modelled in this study are divided into two categories: *endogenous* (local) and *exogenous* (imported). Endogenous resources are those produced locally; they are predominantly renewable and include solar, wind, hydro, geothermal, and biomass energy. A notable exception is waste, which, although locally available, represents the only non-renewable endogenous resource. In the model, these resources are constrained by their maximum potential available within the national territory.

Exogenous resources refer to energy imported from abroad, such as electricity, hydrocarbons, synthetic fuels, and uranium. They are characterised in the model by an import price and a maximum supply limit, reflecting both market constraints and geopolitical considerations.

Local resources (Endogenous)

Photovoltaic solar potential is mainly constrained by the availability of suitably oriented surfaces, estimated between 40 and 60 GW. Wind energy potential is assessed at 10 GW onshore and 6 GW offshore, though estimates vary widely: some studies suggest 7.6–24.5 GW for onshore wind and 613–774 MW for offshore, depending on the energy return on investment (EROI) and capacity factors. These discrepancies reflect both technological uncertainties, such as taller turbines accessing steadier winds, and social constraints, including local opposition to projects.

Hydropower is nearly saturated, with only a marginal residual potential of about 120 MW. Geothermal energy lacks robust potential estimates; the Balmatt pilot project, launched in 2015, could deliver 4–5 MW of electricity, but in the absence of reliable data, geothermal is excluded from the reference scenario. Its potential order of magnitude indicates it would remain a marginal primary source. For heat production, the model also considers solar thermal energy (centralised and decentralised), each with a theoretical potential of 70 GW, also surface-limited like photovoltaic solar.

Biomass and waste are considered separately. Fossil waste (plastics, etc.) is treated as non-renewable, whereas organic biomass is classified into two types: wet biomass, digestible via biological processes (e.g., food waste, agricultural residues), and woody biomass from lignocellulosic materials (wood, sawdust). In 2015, local

production reached 13.9 TWh for woody biomass and 11.6 TWh for wet biomass, with theoretical potentials of 23.4 TWh and 38.9 TWh respectively. These limits, included in the model, comply with European Commission sustainability criteria, accounting for land use and associated production emissions.

Despite this diversity, the overall potential of endogenous resources remains limited, requiring their careful optimisation in any energy transition pathway.

Table 3.1: Installed capacity (2015) and potential of endogenous renewable technologies, from G. Limpens thesis [25]

Technology	**2015 [GW]**	**Maximum potential [GW]**
Electricity production		
Photovoltaic	3.85	≈ 60
Onshore wind	1.18	10
Offshore wind	0.69	6
Hydro river	0.11	0.12
Geothermal	0	≈ 0
Heat production		
Geothermal	≈ 0	≈ 0
Centralised solar thermal	0	≈ 70
Decentralised solar thermal	0	≈ 70

Table 3.2: Available potential and usage of renewable, from G. Limpens thesis [25]

Resource	**2015 [TWh]**	**Maximum potential [TWh]**
Synthetic fuels		
Bioethanol	0.48	0
Biodiesel	2.89	0
SNG	0	0
Hydrogen	0	0
Biomass		
Woody biomass	13.9	23.4
Wet biomass	11.6	38.9
Non-renewable		
Waste	7.87	17.8

Imported resources (Exogenous)

In addition to local resources, the Belgian energy system relies heavily on imported resources, including fossil fuels (gasoline, diesel, natural gas, uranium, coal) and their renewable counterparts (biofuels, hydrogen, synthetic fuels). In the model, these imports are assumed to be unlimited, except for electricity and coal, which are subject to specific constraints. Fossil fuel prices are expected to rise over time, while renewable alternatives are assumed to become cheaper. Uranium is an exception, with a constant price.

Renewable fuels are produced either from biomass (biofuels) or from electricity (electrofuels). In the model, import prices for renewable fuels are set equal to their production costs, without distinction between the two pathways. Although future energy prices remain uncertain, these assumptions are based on literature and European institutional data to ensure consistent transition scenarios.

3.1.2 Accounting of the emissions

As presented in Section 2.2, the gwp_{op} parameter represents the direct and indirect emissions associated with the production, transport, and combustion of resources.

Table 3.3: Operational global warming potential and availability of resources used in the model for 2050

Category	**Resource**	Availability [GWh/y]	gwp_{op} [ktCO_2-eq/GWh] 2050
Non-renewable – Fossil fuels			
	Gasoline	10^{15}	0.3448
	Diesel	10^{15}	0.3148
	LFO	10^{15}	0.3115
	Natural gas	10^{15}	0.2666
	Coal	33355	0.4014
Non-renewable – Other sources			
	Uranium	10^{15}	0.0039
	Waste	17800	0.1501
	Hydrogen	10^{15}	0.3366
	Ammonia	10^{15}	0.2850
	Methanol	10^{15}	0.3500
	Electricity imports	32440	0.0000
Renewable – Biomass			
	Woody biomass	23400	0.0118
	Wet biomass	38900	0.0118
Renewable – Biofuels			
	Bioethanol	10^{15}	0
	Biodiesel	10^{15}	0
	Methane (Re)	10^{15}	0
	Hydrogen (RE)	10^{15}	0
	Ammonia (RE)	10^{15}	0
	Methanol (RE)	10^{15}	0

Parameters under study

As detailed in Section 2.2.1, the current assumption adopted in [25] is to disregard the emissions associated with the extraction, production, and transport of renewable fuels. As shown in the table of available resources for Belgium in EnergyScope (Table 3.3), the gwp_{op} parameter for renewable fuels is therefore set to zero.

The production pathways of these resources are described in detail in the chapter on prospective life cycle analysis.

An additional assumption is that the indirect emissions of other renewable resources are also considered to be zero.

3.1.3 Energy demand and political framework

Energy demand

Table 3.4: End-use demand (EUD) by category and type for 2050, from [25]

EUD	EUT	2050	Units
Electricity	Baseload	73.3	[TWh/y]
	Lighting	31.9	[TWh/y]
Heat	High temperature	56.7	[TWh/y]
	Space heating	92.1	[TWh/y]
	Hot water	22.6	[TWh/y]
Mobility	Passenger	159.3	[Gpkm/y]
	Freight	92.8	[Gtkm/y]
Non energy	Non energy	55.0	[TWh/y]

Political framework

Nuclear

Belgium operates four nuclear reactors distributed over two sites: two at Doel and two at Tihange, with a combined capacity of just under 3.5 GWe. According to the *Belgian Energy Data Overview* [10] (winter 2025 edition), the Doel and Tihange plants accounted for 39.4% of Belgium's gross electricity production in 2023.

Three reactors have been permanently shut down. The first commercial reactor entered service in 1974, marking the start of the country's civil nuclear era. In 2003, a federal law was adopted to phase out nuclear electricity production, mandating the closure of all reactors by 2025 [7].

However, due to the energy context and security-of-supply concerns, this timeline was revised. In March 2022, the Belgian government decided to postpone by ten years the closure of the two most recent reactors,Doel 4 and Tihange 3,allowing their operation until 2035. This was followed, in May 2025, by the formal repeal of the 2003 law by the Belgian Parliament.

A new strategic direction has since been adopted. The government now plans to extend the lifetime of Doel 4 and Tihange 3 until 2045 and is considering the

construction of new reactors. This shift underlines the renewed role of nuclear power in Belgium's energy mix, both as a decarbonisation tool and as a long-term pillar of energy security.

According to [8], the capacity of Doel 4 is 1.026 GWe and that of Tihange 3 is 1.038 GWe.

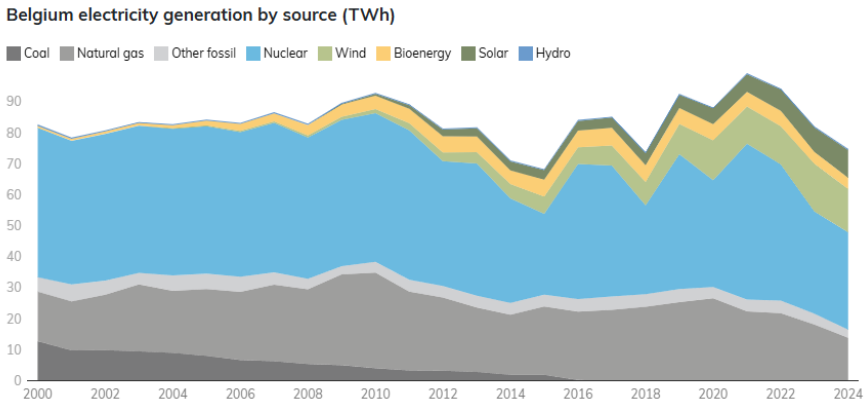


Figure 3.1: Nuclear power plays a significant role in Belgium's electricity generation mix. Source: [4].

An installed nuclear capacity of 2 GW is therefore considered in the case study.

3.2 Reference energetic scenario : Belgium in 2050

3.2.1 Carbon limit

The carbon emission limit adopted in this study is based on the target defined by [9] for Belgium in 2050, set at 10 $MtCO_2$-eq/year as part of the national carbon neutrality objective.

According to [18], significant structural changes occur in the energy system when the total greenhouse gas emissions fall below 9.5 $MtCO_2$-eq/year. In such a case, domestic renewable sources such as solar and wind are largely replaced by imported renewable fuels, while electric technologies are substituted with gas-based technologies. Under this configuration, almost all primary energy comes from renewable fuels, an outcome considered unrealistic due to the large uncertainties in GWP and energy investment data for such fuels, as well as the implausibility of importing approximately 510 TWh/year of them. These observations underline the need for further research to explore low-carbon system configurations with $GWP_{tot} \leq 10$ $MtCO_2$-eq/year.

Furthermore, the findings suggest that renewable fuels play an increasingly central role in meeting mobility and heating end-use demands as GHG emissions targets become more stringent.

3.2.2 Use of imported renewable fuels

Renewable fuels are primarily selected by the model to satisfy the carbon constraint. From an economic perspective, they are generally less attractive than their fossil-based counterparts, with the exception of ammonia and methanol, for which the renewable pathways are actually less costly than the non-renewable alternatives. This outcome is entirely attributable to the price of the feedstock resources, as both renewable and non-renewable variants rely on the same underlying technologies (see the description of layers in Section 2.1.3).

As highlighted in Table 3.5, the use of renewable fuels is therefore driven by the carbon constraint rather than by pure economic competitiveness.

Table 3.5: Levelised production costs in the reference scenario (electricity and high-temperature heat)

Technology	**Resource**	**Cost [M€/GWh]**
Electricity production		
PV	Solar	0.0044
Wind onshore[a]	Wind	0.0060
Wind offshore[a]	Wind	0.0258
Nuclear	Uranium	0.0400
Import electricity	–	0.1049
CCGT ammonia	Ammonia RE	0.1484
Industrial cogen (gas)	Gas RE	0.2568
High-temperature heat production		
Industrial boiler (waste)	Waste	0.0317
Industrial boiler (wood)	Wood	0.0423
Industrial direct electric	Imported electricity	0.1081
Industrial cogen (gas)	Gas	0.1357
Industrial cogen (gas)	Gas RE	0.2465

[a] Excluding curtailment, which has a negligible impact on the cost.

The balance of biofuel imports for the reference scenario is reported in Table 3.6.

Methanol, owing to its favourable economic attractiveness compared to its non-renewable counterpart and its operational $gwp_{\text{op}} = 0$, is entirely selected by the model to synthesise high-value chemicals (HVC) for non-energetic demand.

Ammonia is partly imported for non-energetic demand, where it is consumed directly in its imported form without further transformation. In this case as well,

the entire share is renewable, driven by its superior economic competitiveness relative to the fossil-based equivalent.

Renewable gas is imported to complement fossil gas imports. It is therefore placed in the same layer as non-renewable gas and is not allocated to a specific technology.

Imported hydrogen in the reference scenario mix is entirely renewable. This outcome is explained both by the relatively stringent carbon constraint and by the small price difference with its fossil-based counterpart. Renewable hydrogen is only 4% more expensive than the fossil alternative, with a cost of 0.10 M€/GWh. It is almost entirely used in freight applications, particularly for heavy-duty trucks.

Biodiesel is used in maritime freight. The entire imported diesel share consists of biodiesel, for the same reasons as hydrogen (a price difference of only 15%, with biodiesel costing 0.109 M€/GWh).

Finally, only negligible quantities of bioethanol are imported by the model under the reference scenario.

Table 3.6: Imported renewables fuels in reference scenario over a year

Resources	**Amounts [TWh]**	**Target**
Methanol RE	54.8	NED
Ammonia RE	10.6	NED
	12.7	CCGT
Gas RE	9.1	CHP / Mobility
Bio-diesel	2.7	Freight mobility
Bio-ethanol	0.015	Private mobility
H2 RE	15.6	Freight mobility

Total imported : 105.515 TWh

3.2.3 Nuclear impact

As mentioned in the study by [18], cited in the introduction of this chapter, the presence of nuclear energy reduces the demand for other exogenous resources by more than 60%.

While this significantly alters the overall magnitude of imported renewable fuels, it does not fundamentally change their specific applications or the structural need for renewable fuel carriers, as illustrated in Table 3.7.

Specifically, the consumption of renewable ammonia (AMMONIA_RE) rises by more than 60%, while that of renewable gas (GAS_RE) nearly doubles (+78.3%).

This highlights the compensatory role of renewable molecules in maintaining system balance in the absence of nuclear baseload generation.

Table 3.7: Comparison of Resource Use between NUCLEAR and NON-NUCLEAR Scenarios (Belgium 2050)

Resource	**Used (NUC) [GW]**	**Used (NON) [GW]**	**Diff. [GW]**	**Δ [%]**	**Potential [GW]**
URANIUM	37 188.95	0.00	−37 188.95	−100.0%	∞
METHANOL_RE	54 784.31	54 784.34	+0.03	+0.0%	∞
AMMONIA_RE	23 250.72	37 861.34	+14 610.62	+62.8%	∞
RES_SOLAR	61 259.67	61 389.92	+130.25	+0.2%	∞
RES_WIND	42 540.63	42 713.80	+173.17	+0.4%	∞
CO2_EMISSIONS	34 789.93	36 319.35	+1 529.43	+4.4%	∞
GAS_RE	9 079.30	16 186.39	+7 107.09	+78.3%	∞
GAS	24 186.01	24 730.21	+544.19	+2.3%	∞
ELEC_EXPORT	263.19	126.80	−136.39	−51.8%	∞
RES_HYDRO	480.63	480.75	+0.12	+0.0%	∞
ELECTRICITY	32 439.87	32 439.87	+0.00	+0.0%	32 439.87
WASTE	17 799.99	17 800.00	+0.01	+0.0%	17 800.00
WOOD	23 400.00	23 400.00	−0.00	−0.0%	23 400.00
WET_BIOMASS	38 900.00	38 900.00	−0.00	−0.0%	38 900.00
H2_RE	15 573.26	15 573.20	−0.06	−0.0%	∞

3.2.4 Sankey diagram of reference scenario

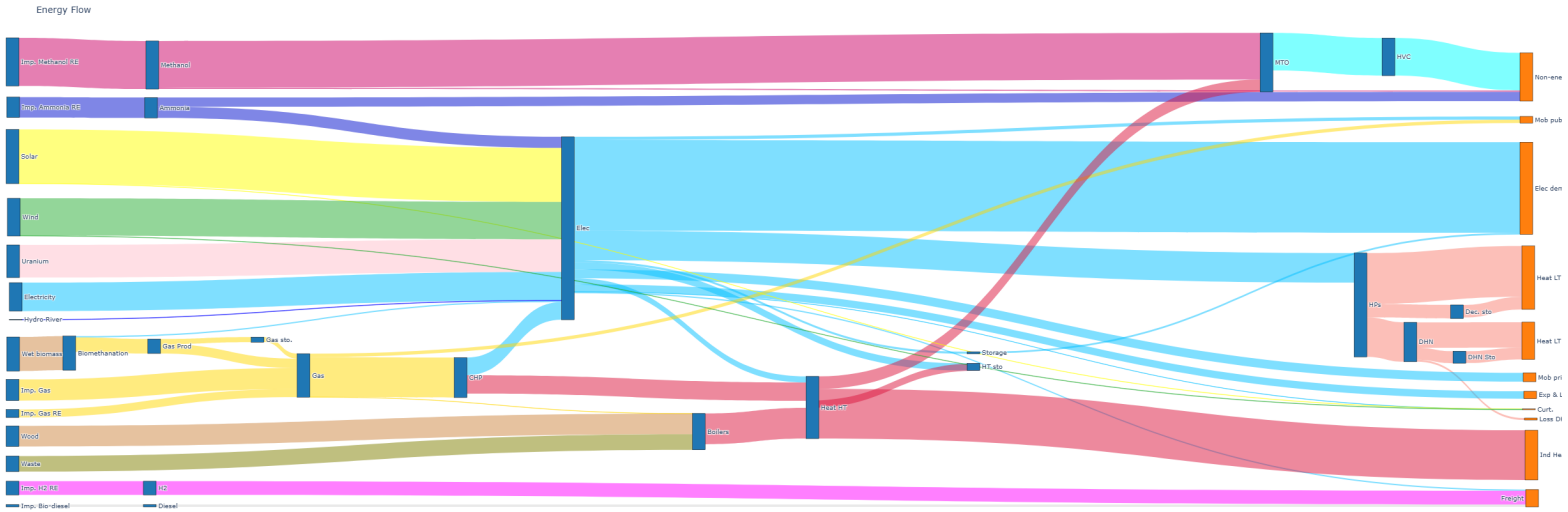


Figure 3.2: Sankey diagram of the reference scenario for Belgium in 2050.

Chapter 4

Tipping points in the Belgian energy scenario

4.1 Tipping point analysis methodology

4.1.1 Conceptual definition and analytical scope

Within the framework of modelling the Belgian energy system by 2050 using the EnergyScope TD model, a *tipping point* refers to a critical threshold in the configuration of the optimal energy mix. Specifically, it denotes a point at which a marginal change in an input parameter,in this thesis, the operational carbon footprint (gwp_{op}) of a renewable resource, leads to a discontinuous shift in the optimal technological or resource pathway.

As long as the parameter remains below this critical value, the model consistently favours a particular solution. However, once the threshold is crossed, even by a small margin, the optimisation abruptly switches to a fundamentally different configuration. This phenomenon is intrinsically linked to the linear and discrete nature of the EnergyScope formulation.

Thus, tipping points underscore the non-linearity of system behaviour in response to linear variations in parameters and highlight the importance of precise characterisation of environmental inputs in energy system modelling.

4.1.2 Scope and methodological clarification

The objective of this chapter is not to determine the tipping points with a high degree of numerical precision. EnergyScope is a scenario-based energy model whose purpose is not to perform unit commitment optimisation, but rather to outline the strategic directions to be followed and to demonstrate the feasibility of a carbon-neutral energy scenario.

Accordingly, the rationale for this chapter is to identify the major shifts in the energy system compared to the reference scenario previously described, resulting from variations in the input parameter gwp_{op} of renewable fuels considered as resources within the EnergyScope framework.

Operational emission variations of these parameters induce a large number of deviations from the reference scenario. However, this chapter does not aim to define the entire space of possible energy system configurations for each input set of gwp_{op}, but rather to identify and characterise the most significant deviations.

Two criteria underpin the selection of the principal changes discussed in this chapter.

The first is the sensitivity of the tipping point, i.e., the extent to which a small change in gwp_{op} leads to a major shift in the optimal configuration. This is exemplified by the transition between electricity production via CCGT units using ammonia and CHP units using gas. A small variation in the gwp_{op} of renewable gas can lead the model to implement more than four times the CCGT ammonia capacity compared to the reference case.

The second criterion is the systemic consequence on the energy scenario.

Finally, it was necessary to determine how to represent a tipping point and which changes to highlight. It was decided to emphasise deviations from the reference scenario in terms of imported resources and energy conversion technologies. For example, when examining the consequences of deviations in the gwp_{op} of imported renewable methane and ammonia, the impacted resources and conversion technologies, namely renewable ammonia, gas, renewable gas, and renewable hydrogen, are highlighted. Secondary effects, such as changes in vehicle types (e.g., trucks), are not included.

This focus is justified by the fact that energy conversion technologies are key amplifiers of systemic changes within the model. A conversion process can influence the internal allocation of resources across different layers of the model. For instance, the Haber-Bosch process, which synthesises ammonia from hydrogen, provides the model with flexibility to respond to an increase in the gwp_{op} of imported renewable ammonia.

4.1.3 Analytical protocol and implementation strategy

In the analyses conducted in this thesis, only the gwp_{op} parameters of biofuel resources were modified. This concerns the following resources: GAS RE, AMMONIA RE, METHANOL RE, H_2 RE, BIODIESEL, and BIOETHANOL.

All other parameters of the model were kept unchanged, including the overall demand, the temporal demand profiles, the number of typical days, and the technical parameters of the technologies. Only the maximum capacity of certain technologies

was set to zero in specific cases, in order to isolate and analyse the interactions between selected technologies.

Methodological approach to tipping point identification

The identification of tipping points in this study is based on a deterministic, pairwise parametric variation methodology. Specifically, the operational carbon intensity (gwp_{op}) of two competing technologies or resources is systematically varied within a defined range, while all other parameters are held constant. This ceteris paribus approach allows for a clear and unambiguous attribution of changes in the system configuration to the parameter under investigation.

Such a targeted strategy contrasts with global sensitivity analyses, such as Monte Carlo simulations or Sobol index decompositions, which, while suitable for identifying key drivers of large-scale uncertainty, often obscure finer structural transitions and context-specific interactions. By isolating specific input parameters, the approach adopted here enables a more granular exploration of discrete shifts in the optimal energy system design, thereby offering clearer insights into the underlying mechanisms of technological substitution and system reconfiguration.

Implementation protocol

To pragmatically assess the structural reconfigurations induced by variations in the operational global warming potential (gwp_{op}) of renewable fuels, a series of isolated parametric analyses was performed.

This targeted approach enables direct comparisons of the model's selection of biofuels and corresponding energy conversion technologies under controlled variations in carbon intensity assumptions. In all scenarios, only the gwp_{op} parameter is modified, while all other model inputs,including infrastructure emissions and system boundaries, remain aligned with the reference configuration.

The procedure follows these steps:

1. **Initial variation:** A systematic variation of the gwp_{op} ratio between two selected biofuels is performed. All other renewable fuels are assigned a gwp_{op} of zero, as in the reference scenario. This isolates the competition mechanism between the two target fuels.

2. **Contextual sensitivity series:** Two additional sets of simulations are conducted in which the gwp_{op} values of all other renewable fuels are fixed at non-zero levels: 2.5×10^4 and 5.0×10^4 $kgCO_2$-eq/GWh, respectively. This allows the model to simulate a carbon-constrained context and prevents solutions from unrealistically relying on zero-emission assumptions. This

upper bound, 5.0×10^4 $kgCO_2$-eq/GWh, is chosen because it lies slightly below 6.5×10^4 $kgCO_2$-eq/GWh, which represents the maximum threshold value for which the model is still able to converge when assigned to all renewable resources in the system.

3. **Tipping point detection:** For each fuel pair, the resulting energy system configurations are analysed to identify abrupt changes in technology deployment. These inflection points are interpreted as tipping points, marking a shift in the optimal strategy due to minor parameter perturbations.

The identification of such tipping points often requires interpreting the trade-offs made by the model between competing technologies. These trade-offs are primarily driven by cost considerations, which are computed as follows.

Cost formulation

The marginal cost associated with a given technology, corresponding to the production of an additional gigawatt-hour, is expressed as:

$$\text{cost} = \frac{1}{cp} \cdot \frac{1}{8760} \cdot (\tau \, c_{\text{inv}} + c_{\text{maint}}) + (\text{ratio} \cdot c_{\text{op}}) \tag{4.1}$$

where the terms are defined as follows:

Table 4.1: Definition of cost parameters

Term	Definition
cp	Capacity factor of the technology (average utilisation rate)
8760	Total number of hours in a year
τ	Annuity factor, computed using the interest rate and lifetime
c_{inv}	Investment cost [M€/GW]
c_{maint}	Annual maintenance cost [M€/GW/year]
ratio	Amount of primary resource required per unit of output [GWh/GWh]
c_{op}	Purchase cost of the primary resource [M€/GWh]

4.1.4 Systemic dynamics and interpretation framework

The methodology adopted in this thesis is based on a central principle: within the EnergyScope framework, renewable fuels can, depending on system constraints, either be substituted by alternative resources or produced domestically from them. For instance, to satisfy the demand for hydrocarbons with chemical value (HVC), the model may select among several pathways:

- import of renewable methanol,

- domestic production via synthetic methanation routes,
- or utilisation of fossil- or bio-based alternatives such as natural gas, crude oil, or biomass.

The model thereby explores a broad solution space of technological configurations and, for each given set of constraints, selects the configuration that minimises the total system cost while satisfying all technical and environmental requirements.

Method for Detecting Tipping Points

To identify the most significant tipping points, transitions likely to substantially alter the structure of the energy mix, a parametric analysis is conducted. This consists of incrementally varying the operational carbon emission factor (gwp_{op}) of one or more imported renewable fuels.

Two Types of System Responses

It is essential to distinguish between two types of dynamics observed when increasing the parameter gwp_{op} for one or more biofuels:

1. **Direct substitution**: one resource or technology is replaced by another to satisfy the same end-use demand (EUD). This reflects an explicit shift in technological choice.
2. **Indirect reallocation**: the system alters the use or import of other resources, not to directly satisfy the same EUD, but to compensate for economic or environmental impacts induced by the resource under analysis.

In the first case, the model arbitrates between functionally equivalent technological chains. In the second, the shift represents a broader systemic response, driven by cost or emission trade-offs at the global system level.

Illustrative Example: Imported Renewable Methanol

Consider the case in which the operational gwp_{op} of imported renewable methanol is increased, while all other parameters remain constant:

- First the system compensates through indirect reallocation: it increases imports of renewable gas at the expense of fossil gas and simultaneously increases imports of renewable hydrogen (H_2 RE).
- Then, at some point, the model entirely ceases imports of renewable methanol. The entire non-energy demand is then satisfied using renewable hydrogen, and fossil gas reappears in the energy mix.

4.2 Imported gas renewable versus imported ammonia renewable

In the reference scenario, a total of 49.6 TWh of gas is consumed. The largest share is directed to CHP units, which use 45.6 TWh for the co-generation of electricity and heat, yielding 20.1 TWh of electricity and 21 TWh of heat. Additionally, 3.9 TWh of gas is dedicated to public mobility.

Regarding its origin, 18.3% (9.1 TWh) of the gas supply consists of imported renewable gas, 48.7% (24.2 TWh) corresponds to imported non-renewable gas, while 33% (16.4 TWh) is produced locally through biomethanation from wet biomass. Overall, imports account for 67% of the total gas consumed in the system.

In the reference scenario, all ammonia consumption originates from imported renewable ammonia. Total imports amount to 23.3 TWh, of which 45% (10.6 TWh) are allocated to non-energy demand (where it is primarily used as a chemical feedstock, notably for nitrogen-based fertiliser productio), while the remaining 55% (12.7 TWh) are used for electricity generation in CCGT units operating on ammonia.

4.2.1 Objective of the Analysis

This analysis aims to investigate the switching behaviour of the EnergyScope model between two competing technological pathways for electricity production:

- Combined Cycle Gas Turbine operating on imported renewable ammonia (CCGT_AMMONIA);
- Industrial cogeneration using either renewable or fossil gas (IND_COGEN_GAS).

In addition, the study explores the broader systemic response to an increase in the gwp_{op} parameters associated with AMMONIA_RE and GAS_RE resources.

These two technologies differ in terms of efficiency, cost structure, heat co-production, and of course the resources they consume. The model may therefore prioritise one resource over the other, depending on the overall carbon emissions constraint and the operational carbon footprint associated with imported renewable ammonia and renewable gas.

The objective is to determine under which conditions, particularly as a function of the operational carbon emission factor (gwp_{op}) of the associated resources, the model prefers:

- renewable imported ammonia as the primary energy carrier;
- gas (renewable or fossil) as the primary energy carrier;

- or a mixed allocation, including the possibility of shifting toward a third energy carrier such as renewable hydrogen.

To this end, two analytical frameworks are explored, as explained in Section 4.1.3 :

1. A *ceteris paribus* analysis, in which only the gwp_{op} values of renewable ammonia and renewable gas are varied, while all other renewable fuels remain carbon-neutral. This isolates the relative effect of the two energy carriers.

2. Two contextual analyses are considered, in which the other renewable fuels are also assigned non-zero carbon impacts. This configuration highlights the behaviour of the model under a more restrictive carbon context, where no resources are assumed to have zero emissions.

4.2.2 Overview of the technologies

Cogeneration, or combined heat and power (CHP), simultaneously produces electricity and heat from a single fuel source within an integrated system. By generating both energy carriers with the same input, CHP can reach efficiencies of up to 85%, reducing energy costs and CO_2 emissions compared to separate production. It is a mature and widely implemented technology.

The use of ammonia in CCGT is still emerging, with projects such as Europe's first ammonia-fired power generation facility at the Whitegate CCGT power station in Cork, Ireland [17]. Gas and ammonia CCGT are expected to have comparable costs and lifetimes, with efficiency being the main difference: 50% for ammonia versus 63% for gas CCGT [5].

The main characteristics of the two technologies are reported in Table 4.2.

Table 4.2: Technical and Economic Characteristics of CCGT_AMMONIA, IND_COGEN_GAS, and SYN_METHANATION

Technology	**Output/Input**	**Value**	**Unit**	c_{inv} [M€/GW]	c_{maint} [M€/GW/y]	**Lifetime** [yr]	c_p [-]	**Specific FEC Cost** [M€/GWh]
CCGT_AMMONIA	Ammonia (input)	−1.952	GWh	750.87	19.02	25	0.63	$0.1\overline{484}$
	Electricity (output)	1	GWh					
IND_COGEN_GAS	Gas (input)	−2.17	GWh	1309.8	84.19	25	0.85	0.256
	Electricity (output)	0.96	GWh					
	High-temp. heat (output)	1	GWh					0.246
SYN_METHANATION	Hydrogen RE (input)	−1.2	GWh	957.07	27.16	20	0.95	0.1312
	CO_2 Captured (input)	−0.2	GWh					
	Gas (output)	1	GWh					
	Heat Low T. (output)	0.3	GWh					

4.2.3 Observations

First co-variation

In the first co-variation exercise, where only the operational global warming potentials (gwp_{op}) of imported renewable ammonia and imported renewable gas are simultaneously varied, the optimisation framework exhibits a pronounced inclination towards the integration of imported renewable gas and renewable hydrogen within the energy mix. This preference persists except in scenarios where the gwp_{op} associated with renewable gas surpasses that of renewable ammonia by a substantial margin. Hydrogen is utilised for the synthesis of synthetic natural gas through the methanation process. The hydrogen also serves as a precursor for ammonia synthesis via the Haber–Bosch process. The resulting shift between the direct importation of ammonia and its domestic synthesis from imported hydrogen is examined in greater detail in Section 4.3.

Additional sensitivity tests show the following thresholds:

- When the gwp_{op} of ammonia is set to zero, imported renewable gas disappears entirely from the mix once its gwp_{op} exceeds $0.03 ktCO_2\text{-eq/GWh}$.
- With $gwp_{op}(\text{ammonia}) = 0.05 ktCO_2\text{-eq/GWh}$, imported renewable gas drops abruptly from 13.33TWh at $gwp_{op}(\text{gas}) = 0.08 ktCO_2\text{-eq/GWh}$ to 0TWh at $gwp_{op}(\text{gas}) = 0.09 ktCO_2\text{-eq/GWh}$. At this tipping point, the model begins importing renewable hydrogen for methanation to replace the lost gas supply.

Subsequently, for increasing values of gwp_{op} associated with renewable ammonia, the optimisation model consistently phases out the use of renewable gas, when the gwp_{op} of renewable gas reaches 0.09.

The model begins to synthesise gas via synthetic methanation when the gwp_{op} values of both AMMONIA_RE and GAS_RE exceed 0.05 $ktCO_2\text{-eq/GWh}$. Under these conditions, the installed capacity of `SYN_METHANATION` reaches a maximum of 2.21 GW.

Finally, once $gwp_{op}(\text{ammonia})$ surpasses $0.10 ktCO_2\text{-eq/GWh}$, ammonia is no longer selected for electricity generation in any scenario. The installed capacity of ammonia-fuelled CCGTs falls to zero, regardless of the gwp_{op} assigned to other biofuels.

Ammonia is then only imported to satisfy non-energy demand, where it is used as a fertiliser or as a basic chemical feedstock.

When the carbon constraint on the system becomes sufficiently stringent, the model may opt to produce ammonia domestically using hydrogen through the Haber-Bosch process. Cela fera l'objet d'une étude détaillée dans la section 4.3

Second and third co-variation

In these analyses, the gwp_{op} values of the four other biofuels are fixed at 0.025 and 0.05 $ktCO_2$-eq/GWh, respectively.

These results corroborate the trends observed in the first analysis, where the gwp_{op} values of all other biofuels were set to zero.

However, by increasing the perceived carbon constraint in the model, through the assignment of a non-zero carbon weight to all biofuels, the system responds by significantly increasing hydrogen imports (up to 70% more hydrogen imported when all other biofuels are set to 0.05 $ktCO_2$-eq/GWh).

Moreover, under these conditions, all imported gas is of renewable origin, indicating a complete substitution of fossil-based gas.

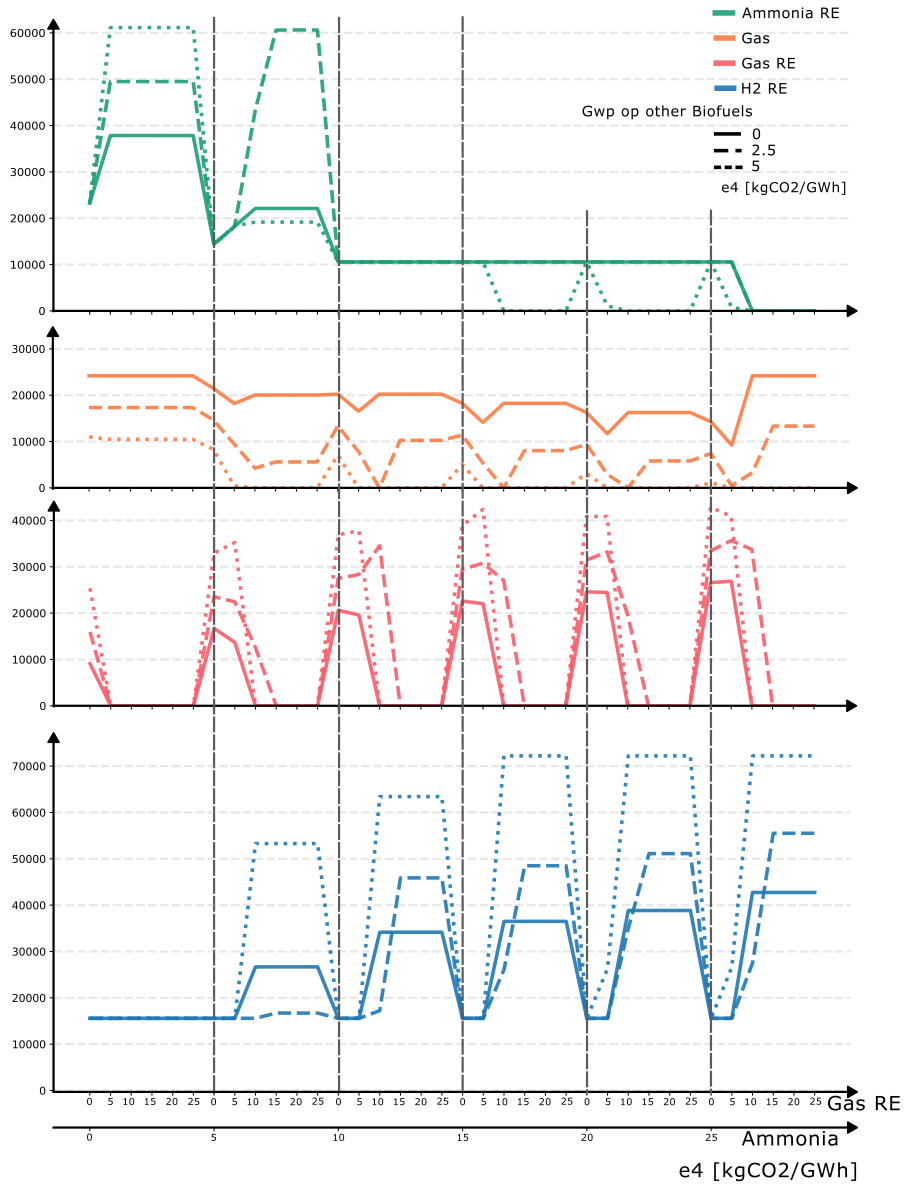


Figure 4.1: Beyond 0.10ktCO_2-eq/GWh renewable ammonia is no longer used for electricity generation.

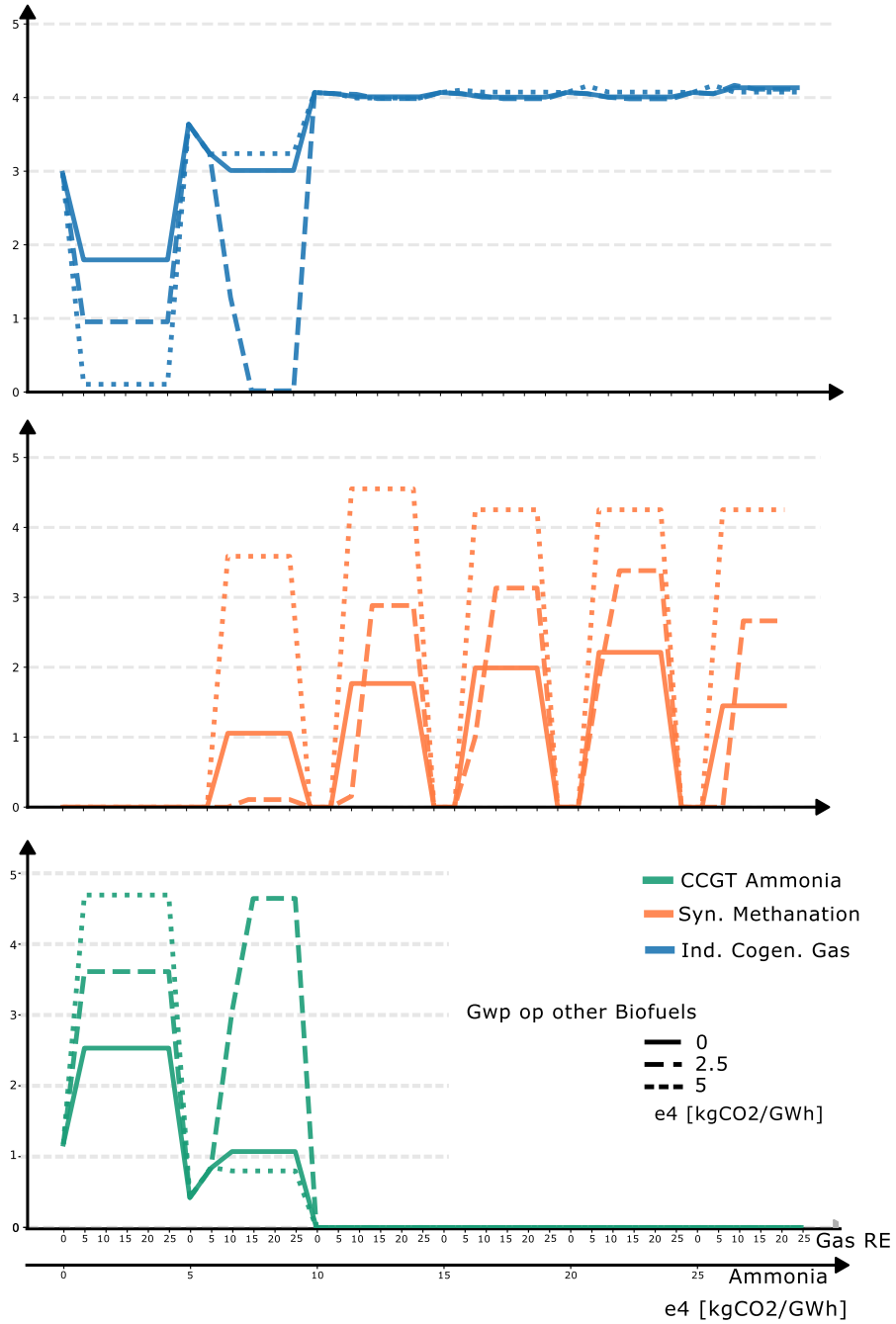


Figure 4.2: The installed capacity of industrial gas cogeneration remains constant at 4 GW across all variations of gwp_{op}.

4.2.4 Synthesis of observed systemic responses

For a gwp_{op} value of imported renewable ammonia exceeding 0.1 $ktCO_2$-eq/GWh, the model no longer deploys any CCGT_AMMONIA units and restricts ammonia imports solely to non-energetic demand.

In parallel, the model systematically installs approximately 4 GW of IND_COGEN_GAS capacity when only non-renewable gas is available. This behaviour appears consistently across model outputs and represents a 25% increase compared to the capacity installed in the reference scenario.

Furthermore, under increasing gwp_{op} values for biofuels, particularly when the carbon intensity of gas is set to twice that of ammonia, the model deploys SYN_METHANATION units in the range of 1.45 to 4.2 GW. This contrasts with the reference scenario, in which no methanation units are installed.

4.3 Imported ammonia versus Haber-Bosch

4.3.1 Objective of the Analysis

This section investigates under which conditions the model opts to produce ammonia via the Haber-Bosch process rather than importing it.

The Haber-Bosch process is a chemical method for synthesizing ammonia through the hydrogenation of gaseous nitrogen.

In the EnergyScope framework, the gwp_construct parameter for the Haber-Bosch process is set to zero. Thus, the comparison is made between imported ammonia, for which the infrastructure construction impact is included in the life cycle emissions, and locally produced ammonia, for which such construction emissions are not accounted for.

Nonetheless, as the model only selects local ammonia production under extreme constraints, and given that implementing a $gwp_{construct}$ for the Haber-Bosch process would only further reduce its attractiveness, the conclusion remains robust: domestic ammonia synthesis is significantly more expensive and is therefore only chosen in scenarios with stringent carbon constraints.

An important parameter to consider in this tipping point analysis is the gwp_{op} of renewable gas. As shown in Section 4.2, increasing the gwp_{op} of ammonia leads EnergyScope to favour a higher share of renewable gas in the energy mix, when it becomes relatively more advantageous.

However, the use of ammonia in the model is bifurcated: one portion is allocated to electricity production, while another is required for non-energetic demand. For the latter, ammonia remains indispensable, meaning the model must either import or produce it locally.

Thus, the present analysis focuses on this specific tipping point, where the model's obligation to meet non-energy-related ammonia demand interacts with the system's carbon constraints and technological trade-offs.

4.3.2 Overview of the technologies

According to the techno-economic assessment, the cost of producing ammonia via the conventional Haber-Bosch process is significantly higher compared to importing renewable ammonia. Specifically, the domestic production cost is evaluated at approximately 0.121 [Meuro/GWh]; see Table 4.3, whereas the import cost of renewable ammonia is estimated at 0.070 [Meuro/GWh]. This indicates that domestic production is nearly 73% more expensive than importing the same energy content in the form of renewable ammonia. The resource used in the Haber-Bosch process for cost calculation is renewable hydrogen (H2_RE), as it is consistently selected by the model across all evaluated scenarios.

The economic implications of this disparity are critical for determining the most cost-effective supply chain configuration, particularly in scenarios aiming to minimize the levelized cost of hydrogen-based derivatives.

Table 4.3: Characteristics of Haber-Bosch process as implemented in Energyscope

Technology	**Flow**	**Value**	**Unit**	c_{inv} [M€/GW]	c_{maint} [M€/GW/yr]	**Lifetime** [yr]	c_p [-]	**Specific FEC cost** [M€/GWh]
	Hydrogen RE	-1.13	GWh					
HABER_BOSCH	Electricity	-0.12	GWh	783.58	15.32	20	1	
	Ammonia	1.00	GWh					0.121

4.3.3 Observations

The model only opts for ammonia synthesis under conditions of extremely stringent carbon constraints.

To observe a realistic selection of the Haber–Bosch process by the model, specific conditions must be met. Assuming a context in which all biofuels other than ammonia and hydrogen exhibit an operational global warming potential (gwp_{op}) of 0.05 ktCO_2-eq/GWh, the model begins to favour the Haber–Bosch synthesis pathway only when the gwp_{op} of imported ammonia exceeds 0.25 ktCO_2-eq/GWh and that of imported renewable hydrogen remains below 0.15 ktCO_2-eq/GWh.

Subsequently, the model tends to replace hydrogen by biodiesel. This substitution is analysed in greater detail in Section 4.6.

Since imported ammonia is itself synthesised from hydrogen (see Section 5.5), it is reasonable to conclude that the conditions under which the model selects

domestic ammonia production via the Haber–Bosch process for local consumption are highly exceptional.

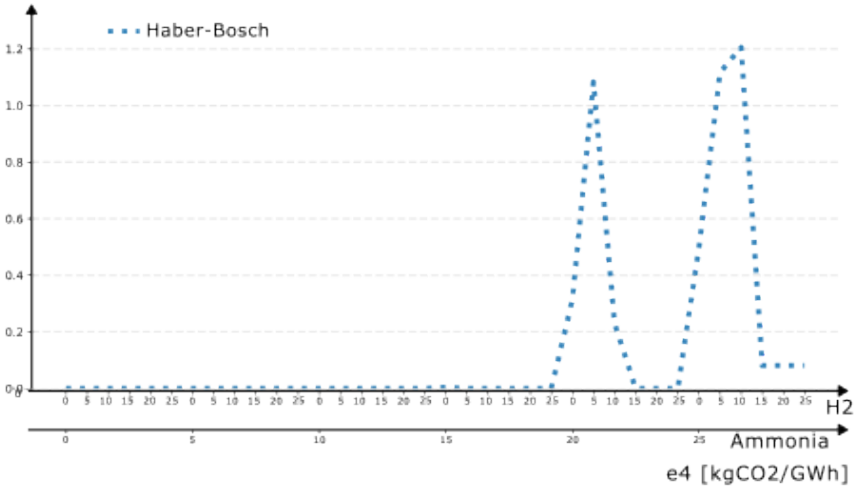


Figure 4.3: Very high gwp_{op} values for ammonia, along with other renewable fuels (here fixed at 0.05ktCO_2-eq/GWh), are required for the model to implement the Haber–Bosch process.

4.4 Imported renewable methanol versus methanol synthesis

In the reference scenario, imported methanol is primarily used to satisfy non-energy demand (NED). Specifically, 53.2 TWh are allocated to the production of high-value chemicals (HVC), while 1.6 TWh are consumed in their pure form.

HVC can theoretically be synthesised from biomass, gas, or oil-based feedstocks. Nevertheless, under all carbon constraint levels and across variations in the gwp_{op} parameters, the model consistently favours methanol as the exclusive precursor for HVC production.

Biomass-to-HVC is the only pathway selected by the model within reasonable ranges of gwp_{op} values, and only under the condition that the capacities of methane synthesis technologies are fixed to zero.

Apart from when biomass to HVC is used, the model systematically imports or produces the full amount of methanol required for HVC synthesis, amounting to 53.2 TWh.

The present analysis therefore focuses on the model's selection among different methanol synthesis pathways, with particular attention to the influence of the gwp_{op}

values associated with imported renewable gas, imported renewable hydrogen, and imported renewable methanol.

Three primary pathways for methanol production are considered:

- **Biomass-to-Methanol**, based on the thermochemical conversion of biogenic feedstocks;
- **Methane-to-Methanol**, using imported renewable methane as the carbon and energy source;
- **Synthetic Methanol Production**, through hydrogenation of captured CO_2 with renewable hydrogen (syn. methanation).

As in the analysis comparing imported ammonia with domestic production via the Haber-Bosch process, the gwp_construction parameter of the methanolation production technologies is set to zero in the input parameters of EnergyScope.

4.4.1 Objective of the analysis

The objective of this analysis is to identify the conditions under which the EnergyScope model favours methanol production through different technological pathways: synthetic methanation from hydrogen, biomass-to-methanol, and methane-to-methanol.

These technologies rely on gas and hydrogen as feedstocks, whose roles become strongly interdependent as their respective gwp_{op} values increase. Under such conditions, it was deemed preferable to isolate these technologies in the sensitivity tests in order to disentangle the relationships between imported methanol and each conversion pathway individually, rather than conflating the interactions among the underlying resources.

4.4.2 Overview of the technologies

The cost of imported renewable methanol is 0.10 [M€/GWh]. Producing methanol through synthetic methanation is slightly less than 50% more expensive, while production via methane-to-methanol is approximately 66% more costly. By contrast, methanol derived from biomass remains the least expensive production pathway. See Table 4.4

For high-value chemical (HVC) production, using renewable methanol as a feedstock entails a cost of 0.1352 [M€/GWh], compared to 0.0945 [M€/GWh] for direct biomass-to-HVC conversion. This cost differential underscores the relative economic disadvantage of methanol-based HVC pathways under the model assumptions.

Table 4.4: Characteristics of methanol synthesis technologies and biomass to HVC

Technology	**Flow**	**Unit**	c_{inv} [M€/GW]	c_{maint} [M€/GW/yr]	**Lifetime** [yr]	c_p [-]	**Specific FEC cost** [M€/GWh]
METHANE_TO_METHANOL	Gas RE	-1.53	546.2	23.88	25	0.85	0.1662
	Methanol	1					
BIOMASS_TO_METHANOL	Wood	-1.57	1764	26.95	20	1	0.0705
	Methanol	1					
	CO2 Industry	0.38					
	Electricity	0.03					
	Heat Low T.	0.35					
SYN_METHANOLATION	Electricity	-0.03	957.07	27.16	20	0.95	0.1312
	Hydrogen RE.	-1.2					
	CO2 Captured	-0.25					
	Methanol	1					
	Heat Low T.	0.08					
BIOMASS_TO_HVC	Wood	-2.31	957.07	27.16	20	0.95	0.0945
	Electricity	-0.03					
	Heat High T.	-0.05					
	HVC	1.00					
	CO2 Industry	0.67					

4.4.3 Observations

It is important to note that these results do not account for the carbon emissions associated with the construction of the infrastructures required for the deployment of the technologies implemented in the model.

Biomass to HVC

When the capacities of the methane-to-biomass, synthetic methanolation and biomass to methanol technologies are constrained to zero, the model converts the entire available wood resource into HVC via the biomass-to-HVC technology. Under this configuration, the renewable methanol imported exhibits an operational climate impact (gwp_{op}) ranging between 0.09 and 0.10 ktCO_2-eq/GWh. Prior to this, the model increases the share of renewable gas in the import mix. This pathway emerges as the most cost-effective solution for the model to satisfy the carbon constraint.

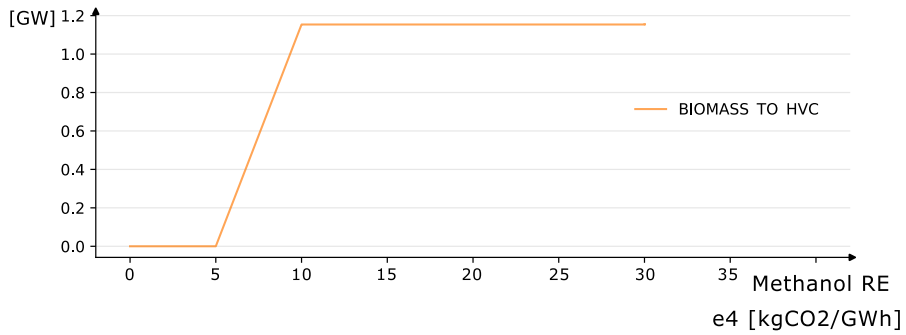


Figure 4.4: A sharper resolution reveals that the switching behaviour occurs abruptly, with no gradual transition, when the gwp_{op} value of renewable methanol lies between 0.09 and 0.10 ktCO_2-eq/GWh.

Biomass to methanol

When the capacities of the biomass-to-HVC, synthetic methanolation, and methane-to-methanol technologies are constrained to zero, a notable shift occurs. This transition is triggered when the gwp_{op} of methanol reaches the interval $[0.09; 0.1]$ ktCO_2-eq/GWh. Concurrently, this change also coincides with the complete elimination of non-renewable gas from the system. At this critical threshold, the model abruptly opts for the installation of 1.71 GW of biomass-to-methanol capacity.

Methane to Methanol

By constraining the capacities of the biomass-to-methanol, biomass-to-HVC, and synthetic methanation technologies to zero, the model is forced to rely exclusively on renewable methanol and renewable gas to satisfy methanol demand.

This configuration results in a sharp increase in the operational gwp_{op} of renewable methanol and renewable gas, as no alternative synthesis pathways remain available. Consequently, the system compensates by producing gas from hydrogen.

The central observation is that, for renewable methanol with $\text{gwp}_{\text{op}} < 0.15$, the model does not deploy any methane-to-methanol capacity. Instead, it increases the share of renewable gas in its import mix in order to comply with the overall emissions constraint.

Conversely, once the gwp_{op} of renewable methanol exceeds 0.15, the model begins to deploy methane-to-methanol capacity in a more stable and substantial manner (see Figure 4.5). Moreover, as soon as the operational emissions of gas surpass those of hydrogen, the system produces gas through synthetic methanation.

In this situation, the model has no further margin of manoeuvre. For $gwp_{op} > 0.2$, renewable methanol is no longer imported, and the choice reduces to either importing renewable gas, when its operational emissions remain lower than those of hydrogen, or producing gas via synthetic methanation when its gwp_{op} becomes higher.

To obtain more accurate thresholds and a clearer picture of the trade-offs between renewable gas imports and synthetic methanation, it would be beneficial to incorporate construction-phase emissions into the analysis.

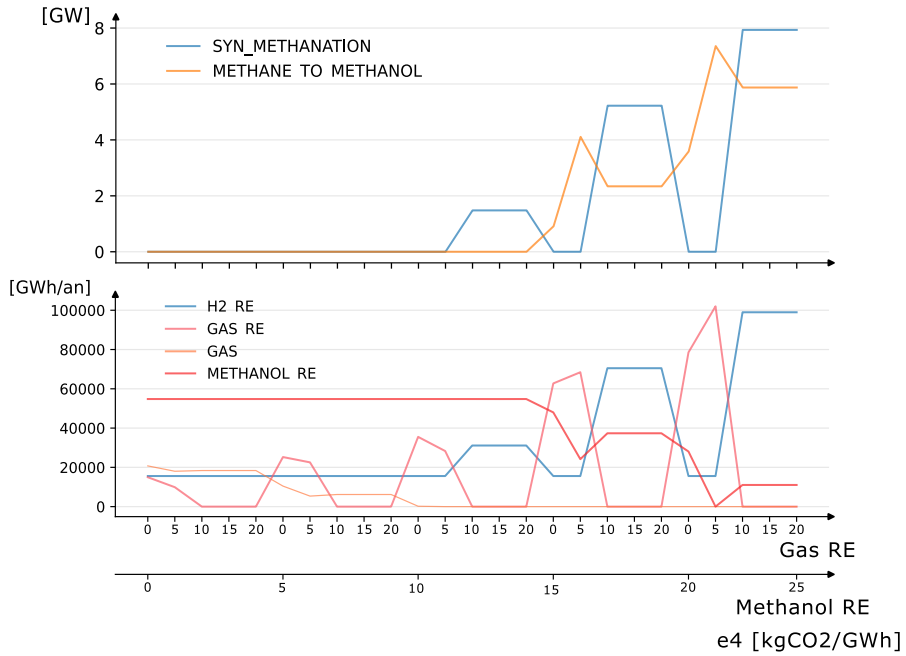


Figure 4.5: Once the gwp_{op} of renewable methanol exceeds 0.2 $ktCO_2$-eq/GWh, the model consistently favours either renewable gas or synthetic methanation, depending solely on their relative gwp_{op} values. At this stage, price no longer plays a decisive role, as the system has no remaining margin of flexibility to comply with the overall carbon constraint.

Hydrogen to methanol (Syn. methanolation)

As shown in Figure 4.6, the model begins to deploy synthetic methanation units once the gwp_{op} of renewable methanol reaches 0.1$ktCO_2$-eq/GWh. This threshold is therefore comparable to that observed for the biomass-to-HVC pathway.

The two sharp decreases in renewable hydrogen imports are due to very limited and punctual imports of biodiesel. This substitution between renewable hydrogen and biodiesel is examined in greater detail in Section 4.6.

Before the gwp_{op} of renewable methanol reaches 0.09 $ktCO_2$-eq/GWh, the model progressively increases the share of renewable gas in the imported gas mix. Then, for values between 0.09 and 0.1 $ktCO_2$-eq/GWh, the system switches towards methanol synthesis solutions.

In conclusion, the dynamics observed here are broadly consistent with those highlighted in Section 4.4.3, confirming that synthetic methanation emerges as a viable alternative once renewable methanol is no longer competitive under stricter carbon constraints.

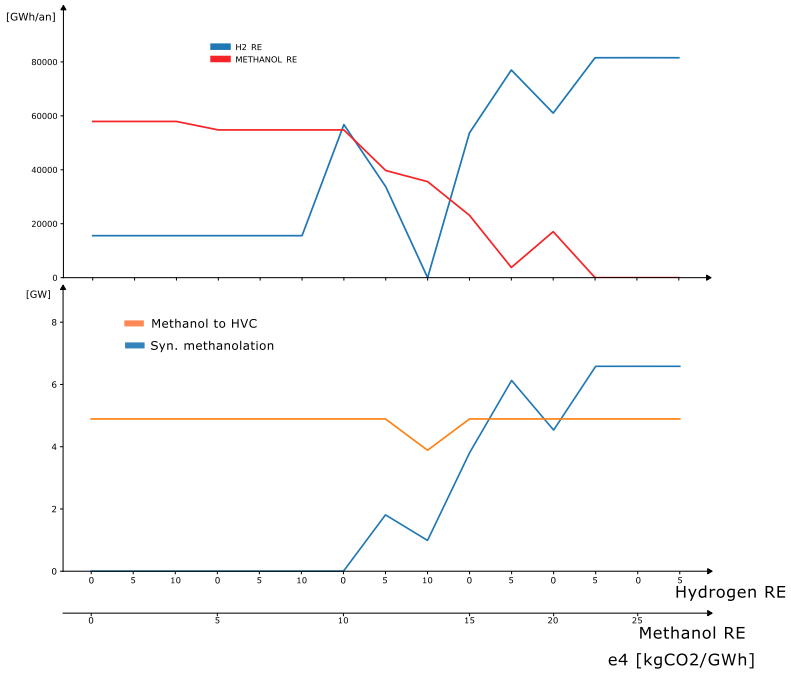


Figure 4.6: As soon as the gwp_{op} of imported renewable methanol exceeds 0.10$ktCO_2$-eq/GWh, the model implements synthetic methanol production.

4.4.4 Synthesis

In general, assigning a non-zero gwp_{op} value to renewable methanol imposes a particularly strong constraint on the model, primarily because of the large quantities of methanol required for HVC production. This makes the system highly sensitive to the assumed carbon intensity of renewable methanol.

The biomass-to-HVC pathway remains limited by the restricted availability of domestic biomass. Moreover, importing biomass would dramatically increase its operational carbon footprint, thereby undermining its role as a low-carbon alternative. As a result, this option plays only a marginal role under most scenarios.

Consequently, the methanol production pathways based on gas and hydrogen emerge as the critical competitors. Their relative deployment is strongly correlated by their operational carbon impacts. The model systematically chooses the option with the lowest gwp_{op} in order to satisfy the global carbon constraint.

4.5 Imported renewable hydrogen versus local hydrogen synthesis

In the reference scenario, hydrogen is entirely imported and renewable and is fully allocated as a fuel for freight transport.

However, EnergyScope includes several technological pathways for hydrogen production: electrolysis of water, biomass conversion, steam methane reforming (SMR) from natural gas, and ammonia cracking.

Based on a sensitivity analysis in which only the gwp_{op} parameter of renewable hydrogen is increased, the model shifts entirely towards producing hydrogen from ammonia. However, this outcome relies on the assumption of zero gwp_{op} for renewable ammonia, which remains consistently favoured by the model given its advantageous cost compared to non-renewable ammonia.

The objective of this analysis is to identify the conditions, in terms of the gwp_{op} values of renewable ammonia and renewable hydrogen, under which the model opts to synthesise hydrogen locally from ammonia.

However, this analysis highlights the use of ammonia for hydrogen synthesis when the difference in their respective gwp_{op} parameters is significant. Yet, ammonia is predominantly produced from hydrogen through the Haber–Bosch process. A plausible justification for this discrepancy could be the substantially higher carbon cost associated with hydrogen transport compared to that of ammonia.

4.5.1 Overview of the technologies

In the resource input parameters of the EnergyScope framework, renewable hydrogen is priced at 0.10M€/GWh, while non-renewable hydrogen costs 0.095M€/GWh. This narrow price difference, combined with the assumption of zero operational emissions for renewable hydrogen, leads the model to systematically favour renewable hydrogen imports.

Producing hydrogen from ammonia (which is always assumed to be renewable, since renewable ammonia is more cost-effective than its non-renewable counterpart) results in an effective hydrogen cost of 0.111M€/GWh (see Table 4.5).

Table 4.5: Technical and economic characteristics of ammonia to hydrogen technology

Technology	**Flow**	**Value**	**Unit**	c_{inv} [M€/GW]	c_{maint} [M€/GW/yr]	**Lifetime** [yr]	c_p [-]	**Specific FEC cost** [M€/GWh]
AMMONIA_TO_HYDROGEN	Ammonia	-1.4	GWh	630.24	58.16	25	0.86	
	Heat High T	-0.15	GWh					
	Hydrogen	1.00	GWh					0.111

Observation

Figure 4.7 illustrates the installed capacities and the imported resources for several ratios of gwp_{op} between ammonia and hydrogen. The gwp_{op} parameters of the other biofuels are fixed at $0.05\,\text{ktCO}_2\text{-eq/GWh}$.

A result that corroborates the findings of Section 4.2 is that, once the system is under strong carbon constraints, approximately 4 GW of industrial cogeneration gas capacity is installed.

The use of ammonia for hydrogen synthesis emerges when the gwp_{op} of renewable ammonia falls below $0.15\,\text{ktCO}_2\text{-eq/GWh}$ and the GWP_{op} of renewable hydrogen exceeds $0.10\,\text{ktCO}_2\text{-eq/GWh}$. In other words, the gwp_{op} of hydrogen must be at least twice as high as that of ammonia which must be under 0.1, for the model to favour this pathway.

Finally, for high values of the gwp_{op} parameter of ammonia, the conclusions drawn in Section 4.3 are confirmed, with ammonia being synthesised via the Haber–Bosch process.

Given that ammonia is, as stated in the introduction of this analysis, predominantly produced from hydrogen, differences in the gwp_{op} parameters of the two resources that would favour hydrogen synthesis from ammonia are relatively unlikely.

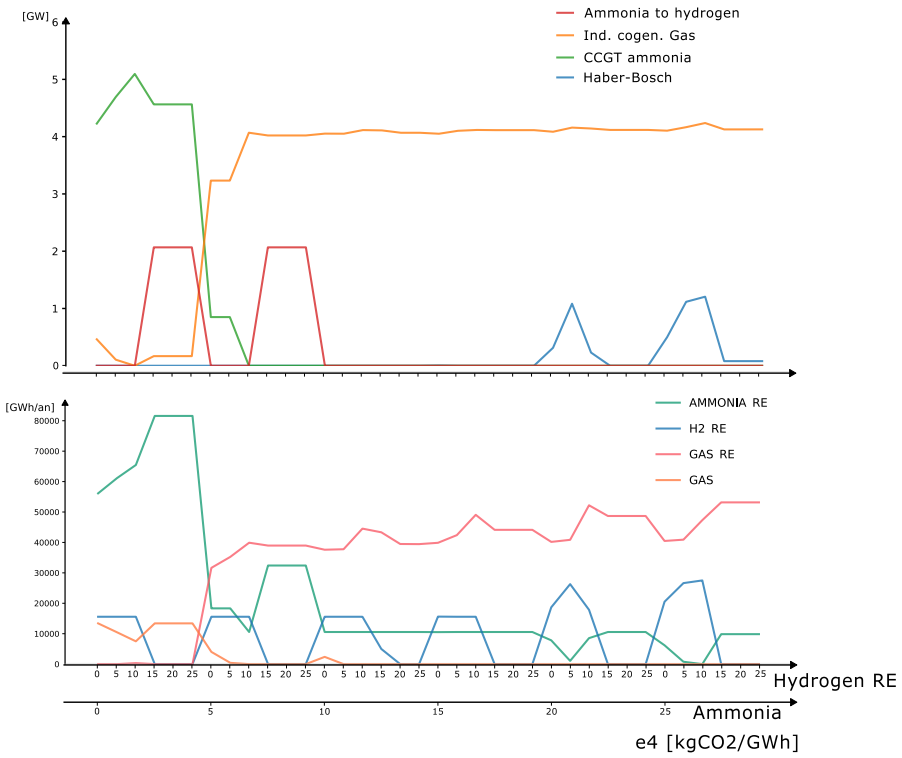


Figure 4.7: The conversion from ammonia to hydrogen occurs exclusively for ammonia gwp_{op} values below 0.1. Furthermore, the gwp_{op} associated with hydrogen is observed to be more than three times and two times higher, respectively, when the ammonia gwp_{op} is set to 0.05 and 0.1 $ktCO_2$-eq/GWh.

4.6 Imported hydrogen versus electrolysis

During the univariate sensitivity analyses of the gwp_{op} parameters for renewable hydrogen, electrolysis was never selected by the model. Instead, the ammonia-to-hydrogen conversion pathway was systematically preferred. However, this latter technology is not yet as mature as electrolysis. Therefore, a complementary analysis was conducted to determine the conditions under which the model would favour electrolysis. In line with the conclusions drawn in Section 4.5, the input parameter corresponding to the capacity of the ammonia-to-hydrogen technology within the EnergyScope framework was set to zero for this purpose.

Nevertheless, hydrogen also competes with biodiesel as a resource in the freight transport sector. The model must choose between hydrogen-powered and biodiesel-powered trucks.

4.6.1 Overview of the technologies

The cost of producing one unit of hydrogen is highly dependent on the electricity price. For instance, when electricity is generated via industrial gas cogeneration using renewable gas, the resulting hydrogen cost is approximately 0.2829£/kWh; whereas with solar electricity, it drops to 0.0113£/kWh. However, it must be noted that the maximum capacities of electricity production technologies are already determined by the model. As such, any additional unit of electricity is produced at the marginal, most expensive cost. Unless a structural reallocation of technologies occurs within the energy system, which is not observed in this scenario, this marginal cost remains high.

This explains why electrolysis is not favoured by the model in the reference scenario. At marginal electricity prices, hydrogen produced via electrolysis is significantly more expensive than imported hydrogen.

Table 4.6: Technical and economic characteristics of hydrogen electrolysis

Technology	**Flow**	**Value**	**Unit**	c_{inv} [M€/GW]	c_{maint} [M€/GW/yr]	**Lifetime** [yr]	c_p [-]	**Specific FEC cost** [M€/GWh]
	Electricity imported	-1.08	GWh					
H2_ELECTROLYSIS	Heat High T	-0.19	GWh	506.33	13.92	15	0.9	
	Hydrogen	1.00	GWh					[0.01 - 0.2829]

4.6.2 Observations

In Figure 4.8, the gwp_{op} of biofuels is set to 0.05, and the capacity of the ammonia-to-hydrogen technology is fixed at zero.

No electrolysis is selected by the model when the gwp_{op} of hydrogen is below 0.15. Electrolysis begins to be partially deployed when the gwp_{op} of hydrogen lies between 0.15 and 0.2, with an installed capacity reaching 0.22GW. When the gwp_{op} of hydrogen exceeds 0.2, all hydrogen is produced via electrolysis.

Biodiesel is selected by the model when its gwp_{op} is at least three times lower than that of hydrogen. This leads to a structural shift, whereby diesel-powered trucks are introduced. However, they never fully replace hydrogen-powered trucks within the model.

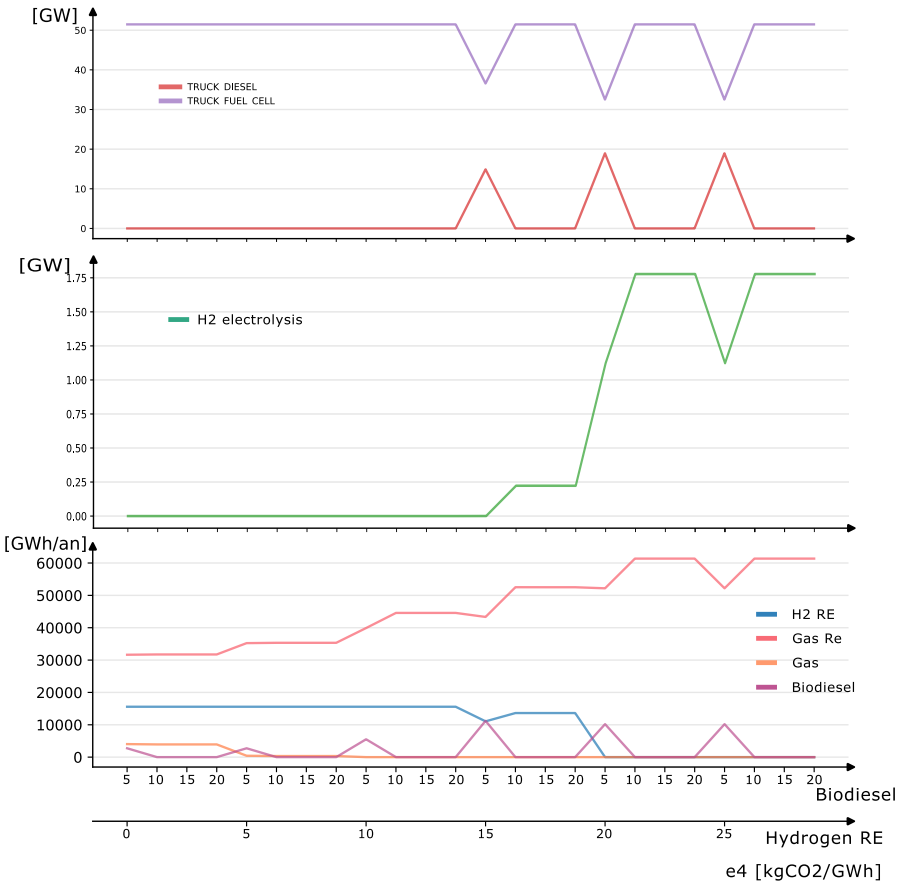


Figure 4.8: No electrolysis is selected by the model when the gwp_{op} of hydrogen is below 0.15

4.7 Synthesis of Emerging Patterns and Structural Shifts

This section delineates key transition thresholds in the Belgian energy system as influenced by the operational global warming potential (gwp_{op}) of critical energy vectors. The synthesis emphasizes discontinuities in technology choices, signifying structural bifurcations in optimal energy pathways.

Transition between renewable gas and renewable ammonia

The comparative analysis of renewable gas and ammonia reveals sharp thresholds in technology adoption:

- When $\text{gwp}_{\text{op}}(\text{gas}) > 0.09$, renewable gas is phased out. This is concomitant with the deployment of SYN_METHANATION up to its capacity ceiling (4.1 GW), alongside a transition towards molecular hydrogen (H_2) and consistant import of non renewable gas. The economical optimum phase out reneawble gas.
- When $\text{gwp}_{\text{op}}(\text{ammonia}) > 0.10$, all CCGT_AMMONIA units are abandoned. In such cases, ammonia is retained solely within the nitrogen–energy domain (NED), indicating a specialization of its use.

Imported versus locally synthesized ammonia

A shift from imported ammonia to local synthesis via the Haber–Bosch process emerges under specific conditions:

- If $\text{gwp}_{\text{op}}(\text{ammonia}) > 0.20$ and $\text{gwp}_{\text{op}}(H_2) < 0.15$, and $\text{gwp}_{\text{op}}(\text{other biofuels}) = 0.05$ local ammonia production is initiated via the Haber–Bosch route.

Methanol importation versus local synthesis

Both biomass-to-HVC and biomass-to-methanol technologies are selected when the operational global warming potential of methanol (GWP_{op}) increases from 0.09 to 0.1 $\text{ktCO}_2\text{-eq/GWh}$. This deployment occurs as a last-resort measure, when the model has exhausted all other feasible alternatives.

- When $\text{gwp}_{\text{op}}(\text{methanol}) \approx 0.09{-}0.10$, a sudden investment in `SYN_METHANOLATION` is observed.
- If $\text{gwp}_{\text{op}}(\text{methanol}) > 0.20$, methanol importation is entirely supplanted by either renewable gas or synthetic methane.

Imported hydrogen vs ammnonia to hydrogen and electrolysis

Although considering that hydrogen has a greater impact than ammonia constitutes a rather strong assumption, it is nonetheless observed that:

- When $\text{gwp}_{\text{op}}(H_2) > 0.10$ and $\text{gwp}_{\text{op}}(NH_3) < 0.1$, the ammonia to hydrogen conversion pathway is activated. With no electrolysis in the optimum find by the model
- When $\text{gwp}_{\text{op}}(H_2) > 0.15$ and ammonia-to-hydrogen pathway is decommissioned and electrolytic hydrogen production is introduced.

Road freight transport: biodiesel versus hydrogen

The competitiveness of hydrogen against biodiesel in road freight applications is relatively strong :

- When $\frac{\text{gwp}_{\text{op}}(\text{H}_2)}{\text{gwp}_{\text{op}}(\text{biodiesel})} > 3$, diesel-powered trucks re-enter the energy system by supplying .

Chapter 5

Prospective Life Cycle Assessment of renewable fuel supply chains in Europe (2050 Horizon)

5.1 Introduction to prospective LCA

Traditional Life Cycle Assessment (LCA) quantifies all material and energy flows, including emissions, associated with a product or service throughout its entire life cycle, following a consistent methodological framework. It typically relies on a static life cycle inventory (LCI) database, such as *ecoinvent*, which reflects the technologies, industrial practices, and energy mixes at a given point in time. By aggregating impacts from raw material extraction to end-of-life management, this approach enables the calculation of the current environmental footprint. However, it does not account for the temporal dynamics of industrial transformation, and thus cannot capture the progressive shift towards low-carbon, resource-efficient systems.

Over the coming decades, systemic transformations, driven by greater electrification, large-scale deployment of renewable energy sources, improved industrial process efficiencies, and emerging innovations such as direct CO_2 capture, are expected to alter the fundamental parameters underpinning LCI datasets.

Prospective Life Cycle Assessment (pLCA) addresses this limitation by introducing a temporal dimension and coupling static LCI databases with forward-looking scenarios derived from Integrated Assessment Models (IAMs). These models define Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), projecting the evolution of energy systems, industrial sectors, and consumption patterns up to 2050 and beyond [12, 38].

In practice, pLCA constructs dynamic, time-dependent LCI databases by

explicitly modelling the anticipated evolution of both the *foreground system*, the technology or process under investigation, and the *background system*, representing the broader economic and technological context. The procedure begins by modelling the foreground technology using a static background database. For each subsequent time horizon, the background is iteratively updated by replacing conventional processes,such as fossil-based electricity generation, coal-derived steel production, or high-carbon cement manufacturing, with lower-emission alternatives, in accordance with IAM-derived trajectories. These substitutions may include wind-powered electricity generation, low-carbon concrete, and recycled alloy production, reflecting both technological performance improvements and diffusion rates of emerging solutions.

To ensure methodological consistency between the maturity level of the assessed technology and its surrounding technological landscape, the background scenarios must represent anticipated sector-wide developments, encompassing energy production, raw material supply, manufacturing, and waste management. Achieving this requires the formulation of coherent qualitative narratives supported by quantitative modelling, ultimately enabling the construction of dynamic LCI databases that are fully aligned with the envisaged future scenarios.

5.1.1 Methodological framework

IAM prospective scenarios

IAM scenarios describe how the global society, demographics, economic development, greenhouse gas emissions, and other radiative forcings may evolve over the coming century. A distinction must be made between the Representative Concentration Pathways (RCPs) and the *Shared Socioeconomic Pathways* (SSPs).

Representative Concentration Pathways. RCPs specify trajectories of greenhouse gas concentrations and radiative forcing levels without embedding any socioeconomic narratives. They define alternative futures for atmospheric composition and, by extension, the magnitude of global warming expected by 2100.

Shared Socioeconomic Pathways. SSPs provide internally consistent narratives of how global socioeconomic factors may develop, including population dynamics, economic growth, education, urbanisation, and technological change. These pathways form the contextual backdrop against which emission reductions may, or may not, be realised. The SSP framework includes five archetypes: (i) a sustainability-oriented world (SSP1), (ii) a "middle-of-the-road" development trajectory (SSP2), (iii) a fragmented world of regional rivalry (SSP3), (iv) a world

of persistent inequality (SSP4), and (v) a fossil-fuel intensive world with rapid growth (SSP5).

The RCPs were first finalised for use in the IPCC Fifth Assessment Report, whereas the more elaborate SSP framework was published in 2016 and is being applied in the Coupled Model Intercomparison Project Phase 6 (CMIP6), which underpins the IPCC Sixth Assessment Report [22].

According to [22], the SSP1 (sustainability-taking the Green Road) pathway depicts a world gradually but consistently transitioning towards more sustainable practices. It is characterised by inclusive development, improved management of global commons, and strong investments in education and health. Economic growth increasingly shifts towards human well-being rather than material consumption, while resource and energy intensities decline.

In contrast, SSP5 (Fossil-fuelled development-Taking the Highway) describes a world relying heavily on competitive markets and rapid technological progress. Despite advances in human capital and global integration, this scenario assumes the continued exploitation of abundant fossil resources and highly energy-intensive lifestyles. While local environmental problems are mitigated, the reliance on carbon-intensive development results in substantial climate challenges.

As highlighted by [6], both SSP1 and SSP5 project relatively optimistic human development trajectories, including rapid economic growth, strong institutions, and substantial social investments. However, their divergence lies in energy intensity and resource use: SSP1 emphasises low-carbon sustainability, whereas SSP5 assumes fossil-driven growth. By contrast, SSP2 represents an intermediate pathway where current socio-economic trends persist without major disruptions.

The main features of the climate scenarios considered in this study are summarised in Table 5.1. This table highlights the correspondence between socio-economic narratives (SSPs), carbon budget constraints, and Representative Concentration Pathways (RCPs). It illustrates the wide span of possible futures, ranging from stringent mitigation trajectories consistent with the Paris Agreement (e.g. SSP1-PkBudg500, aligned with RCP1.9) to fossil-fuel intensive development (e.g. SSP5-Base, approximating RCP6.0).

Scenario	Definition	Temperature in 2100	RCP Correspondence
Base	Reference scenario without additional intervention beyond historical trends; equivalent to RCP6.0 in most cases.	+2.2 °C (SSP1-Base) to +4.5 °C (SSP5-Base)	RCP6.0
NPi	Includes only climate policies already adopted and in place in each country at the time of modelling.	+1.9 °C (SSP1-NPi) to +4.0 °C (SSP5-NPi)	–
NDC	Accounts for formal commitments submitted by each country under the Paris Agreement for 2030 or 2050.	+1.7 °C (SSP1-NDC) to +3.0 °C (SSP5-NDC)	–
PkBudg1150	Sets a maximum total carbon budget of 1150 $GtCO_2$ emitted after 2010, aligned with trajectories limited to +2 °C.	+1.3 °C (SSP1-PkBudg1150) to +1.6–1.8 °C (SSP2-PkBudg1150)	RCP2.6
PkBudg500	Caps the carbon budget at 500 $GtCO_2$ emitted after 2010, consistent with a +1.5 °C target.	+1.0 °C (SSP1-PkBudg500) to +1.2–1.4 °C (SSP2-PkBudg500)	RCP1.9

Table 5.1: Summary of climate scenarios and their main characteristics.

5.1.2 Premise

The open-source Python library premise, short for *PRospective EnvironMental Impact asSEssment*, constitutes a methodological advancement in the integration of future-oriented scenarios into Life Cycle Assessment (LCA). It builds upon the foundational work of Mendoza Beltran et al. [29] and Cox et al. [16, 15].

Premise enables the generation of prospective Life Cycle Inventory (pLCI) databases by modifying existing background data from the ecoinvent v3.6 to 3.10 databases in accordance with projections from Integrated Assessment Models (IAMs), such as REMIND and IMAGE. These modifications may be implemented under both “cut-off” and “consequential” system models, thereby aligning life cycle inventories with selected Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs).

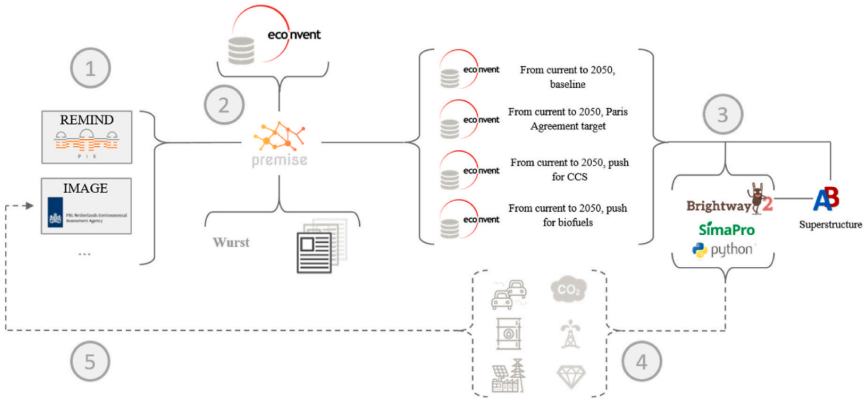


Figure 5.1: Overview of the IAM-LCA coupling workflow, from [37]

The tool applies region-specific and sector-specific transformations to key energy- and emission-intensive activities within the inventory database. These transformations include alterations in technology efficiencies, energy carrier mixes, carbon intensities, and the market penetration of emerging technologies in sectors such as electricity generation, cement and steel production, road transport, and fuel supply [37].

5.1.3 EcoInvent database

Allocation cut-off by classification: The system model "Allocation, cut-off by classification," or the cut-off system model, is based on the recycled content, or cut-off, approach. In this system model, wastes are the producer's responsibility ("polluter pays"), and there is an incentivization to use recyclable products, that are available burden free (cut-off). The underlying philosophy of this approach is that primary (first) production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for the provision of any recyclable materials. As a consequence, recyclable materials are available burden-free to recycling processes, and secondary (recycled) materials bear only the impacts of the recycling processes. For example, recycled paper only bears the impacts of waste paper collection and the recycling process of turning waste paper into recycled paper. It is free of any burdens of the forestry activities and processing required for the primary production of the paper

Allocation at the point of substitution: The system model "Allocation at the point of substitution" is also known as the APOS system model. It follows an attributional approach in which the responsibility over wastes (burdens) is shared

between producers and subsequent users benefiting from the treatment processes by using valuable products generated in these.

Substitution, consequential, long-term: In this master thesis, the consequential life cycle assessment framework is adopted. This methodological choice is grounded in the capacity to account for system-wide changes and to reflect the dynamic evolution of the production mix over time. The consequential approach relocates all by-products to the input side with a negative sign to maintain mass balance, thus avoiding the need for allocation. Consequently, each activity is burdened with the totality of its inputs and emissions.

An essential feature of consequential is the inclusion of substitution effects. By-products that displace the production of equivalent reference products are credited, thereby reducing the overall environmental burden of the activity that generates them.

The selection of the consequential approach is particularly pertinent in the context of energy system modelling, where the interaction between foreground systems (i.e., the specific technologies under study) and background systems (i.e., the broader economic and energy contexts) is dynamic and interdependent. In this regard, the evolution of the production mix, influenced by political, technological, and socio-economic factors (SSP scenarii), justifies the adoption of a modelling paradigm capable of capturing indirect and market-mediated effects.

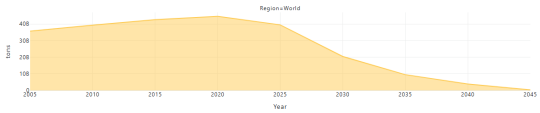
LCI dynamic structuring (superstructure) To address the challenge of managing multiple scenario-specific Life Cycle Inventory (LCI) databases, Steubing et al. [38] propose the *superstructure* approach. This method consolidates all unique flows and processes from various scenarios into a single comprehensive LCI database. Scenario-specific variations are stored separately in a lightweight difference file, allowing for rapid reconstruction of any scenario in memory during LCA calculations. Initially designed for background systems, this structure also supports foreground and hybrid modelling, notably implemented in Activity Browser.

5.1.4 Justification of scenario selection

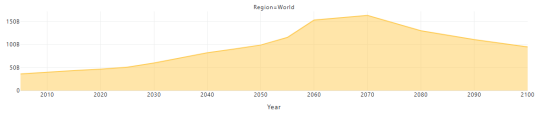
In this work, the REMIND SSP1-PkBudg500 and SSP5-Base scenarios are selected as bounding cases to define the prospective emission range of the fuels under study. The former represents a stringent mitigation pathway consistent with a 1.5 °C carbon budget, while the latter reflects a fossil-intensive baseline trajectory. By focusing on these two contrasted socio-economic futures, the analysis captures the lower and upper limits of greenhouse gas emissions without considering intermediate

pathways such as SSP2, thereby ensuring robust comparisons of renewable gas impacts under divergent policy and technological contexts.

Particular attention is given to ensuring that the analysed production pathways retain their designation as renewable. For instance, electrolytic hydrogen is highly sensitive to the background scenario, since its carbon intensity depends directly on the electricity mix. To preserve the methodological consistency of its classification as a renewable fuel, only the SSP1-PkBudg500 scenario is considered for this pathway. The rationale for this choice is discussed in detail in Section 5.4.1.



(a) A scenario in which cumulative emissions are constrained to 500 $GtCO_2$, corresponding to a 66% probability of limiting global warming to 1.5 °C above pre-industrial levels.



(b) Under the SSP5 scenario, greenhouse gas emissions are projected to more than double by 2050.

5.2 Methodological framwork of this study

The international standard ISO 14040:2006 establishes the general principles and methodological framework for conducting Life Cycle Assessment (LCA), while ISO 14044:2006 specifies the requirements and recommendations for its implementation [3]. These normative documents, widely recognized within the scientific and industrial communities, do not prescribe specific methods or tools for performing LCA. On the contrary, they explicitly acknowledge the absence of a universal methodology (ISO 14040:2006). Their principal function is to provide a common terminology and a harmonized structure for conducting LCA studies, while granting practitioners the flexibility to select the most appropriate tools, databases, and assumptions for their specific context.

5.2.1 Goal and scope definition

Objective and research questions The objective of this section is to quantify the life-cycle climate impacts of alternative renewable gas production pathways under contrasting future energy scenarios. The analysis seeks to provide sufficiently precise order-of-magnitude estimates to enable a robust comparison across different renewable methane pathways, to benchmark these results against their fossil-based counterparts, and to assess how the relative performance of each pathway evolves

as a function of systemic decarbonisation trajectories projected under the SSP scenarios.

System boundaries and functional units The functional unit is defined as 1 GWh of distributed energy carrier delivered at the point of use. This functional unit is employed to present the results, as it enables direct comparison with the pre-existing data in EnergyScope, which are also formulated in terms of energy quantities expressed in GWh.

Although the functional unit adopted in the results is 1 GWh, the production pathways for renewable fuels presented below are expressed per megajoule (MJ) of energy carrier. This choice reflects the prevailing convention in the life cycle assessment literature, where MJ is the most commonly used unit of analysis.

System boundaries are established consistently across all renewable fuel pathways and follow a *cradle-to-gate* perspective.

For biomass-based resources, the assumption of biogenic carbon neutrality is applied. The rationale, scope, and limitations of this assumption are discussed in detail in Section 5.2.3.

Temporal and geographical coverage The assessment is performed as a prospective snapshot for the year 2050, considering two contrasting socio-economic futures represented by the SSP1 and SSP5 scenarios. Since the analysed pathways represent imported energy carriers, the system boundaries in the ecoinvent database are aligned with processes defined at the European level.

Impact categories considered In line with the objectives of this study, the analysis focuses primarily on the climate change impact category, expressed as Global Warming Potential over a 100-year horizon (GWP_{100}) in $kgCO_2$-eq, following the characterisation factors of the IPCC. See Section 5.2.3 This choice is motivated by the central role of greenhouse gas emissions in energy and climate policy, as well as by the need for comparability with the socio-economic scenarios (SSP1 and SSP5) that explicitly target carbon budgets.

Other environmental impact categories, such as acidification, eutrophication, particulate matter formation, land use, and water scarcity, are acknowledged as relevant in the broader context of life cycle sustainability assessment.

Consequently, the scope of this thesis remains centered on carbon while recognising that future multi-criteria assessments may yield complementary insights into trade-offs and co-benefits across impact categories.

5.2.2 Life Cycle Inventory (LCI) development

Top-down LCI modelling strategy In this study, the Life Cycle Inventory (LCI) for each energy pathway is constructed using a top-down modelling approach. This methodology begins with macro-level, aggregated data sources such as sectoral production statistics.

Furthermore, for processes involving electricity consumption or generation, the carbon intensity of the electricity mix is parameterised according to scenario-specific values derived from IAM-integrated datasets via the remise toolchain. This integration ensures coherence between foreground technology pathways and background system transformations projected under different Shared Socioeconomic Pathways (SSPs).

Data sources and processing This study relies on activities from the ecoinvent_v3.9.1_cutoff_ecoSpold02 database, which are prospectively updated using the premise framework under the SSP1-PkBudg500_2050 and SSP5-Base_2050 scenarios [37]. Foreground data are harmonised with these background transformations to ensure methodological consistency across pathways.

Additional transport burdens related to feedstock supply chains and the import of final products are included separately and are documented in the respective pathway sections and annexes.

5.2.3 Life Cycle Impact Assessment (LCIA)

Equivalent CO_2 emissions

To enable the quantification and comparison of the climate impacts of various greenhouse gas emissions, it is necessary to adopt a common climate metric that reflects their radiative effects on the Earth's energy balance. In accordance with the methodology presented by the Intergovernmental Panel on Climate Change (IPCC, 2013) [1], the Global Warming Potential over a 100-year horizon (GWP_{100}) has become the standard metric for expressing emissions of different gases on a unified scale, referred to as CO_2 equivalent emissions.

The GWP is defined as the time-integrated radiative forcing due to the emission of 1 kg of a given gas, relative to that caused by 1 kg of carbon dioxide (CO_2), over a specified time horizon H.

Formally, this is expressed as:

$$\mathrm{GWP}_H(\mathrm{gas}) = \frac{\int_0^H RF_{\mathrm{gas}}(t)\,dt}{\int_0^H RF_{\mathrm{CO_2}}(t)\,dt} \tag{5.1}$$

where $RF_{\text{gas}}(t)$ and $RF_{\text{CO}_2}(t)$ represent the instantaneous radiative forcing (in $\text{W} \cdot \text{m}^{-2}$) at time t following a unit pulse emission of the considered gas and of CO_2, respectively. The parameter H denotes the time horizon (in this work $H = 100$ years in climate assessments).

Biogenic carbon neutrality

The analysis conducted by [43] highlights that the explicit consideration of biogenic carbon within the input–output flows, in accordance with life cycle assessment (LCA) principles, can lead to results that differ significantly from those based on the assumption of biogenic carbon neutrality, with deviations ranging from -86% to +50%. Nevertheless, within the scope of this thesis, the purpose of the prospective LCA is to provide an order-of-magnitude estimation rather than an exhaustive and highly detailed carbon accounting. Furthermore, the most substantial discrepancies reported in [43] are associated with extreme assumptions, such as complete anaerobic decomposition of biomass residues, considerable methane leakage, or substantial differences in system boundaries (e.g., cradle-to-gate versus cradle-to-grave), which are not representative of the modelling framework adopted here. Given that in this study biogenic carbon flows are assumed to be rapidly offset by biomass regrowth and that methane emissions during the use phase are negligible, the assumption of biogenic carbon neutrality remains a reasonable and conservative simplification for prospective analysis.

Another frequently raised argument against the assumption of carbon neutrality for biomass relates to its opportunity cost, particularly in the wood processing industry. In many cases, residual biomass,such as sawdust, bark, or other wood waste, is already utilised on-site or locally for thermal applications, thereby displacing heat that would otherwise be produced from fossil fuels. This substitution effect contributes to reducing overall greenhouse gas emissions.

However, when such residues are redirected towards syngas or biofuel production, they are no longer available for their original heat-generating purpose. As a result, the heat that was previously supplied by biomass may need to be replaced by alternative sources, which could include fossil-based fuels. This indirect substitution can lead to a rebound in emissions elsewhere in the system. Therefore, the allocation of biomass resources to new conversion pathways, such as gasification, must be carefully assessed in light of their existing uses and the broader energy system implications.

5.3 Pathways for Renewable Methane Production

This section presents the main technological pathways for renewable methane production. A clear distinction is established between two fundamentally different conversion routes: biological processes, such as anaerobic digestion, and thermochemical processes, including biomass gasification and the Sabatier reaction. These routes differ not only in their operating conditions and feedstock requirements, but also in their environmental impacts, integration potential, and maturity level. The following subsections detail each pathway, outlining the underlying chemical reactions, system boundaries, and modelling assumptions.

5.3.1 Methane production from biomass

The biogas pathway

Anaerobic digestion Anaerobic digestion can process a wide variety of organic feedstocks, ranging from **wet waste streams**,such as sewage sludge, agro-industrial effluents, and animal manure, to dedicated energy crops cultivated specifically for biogas production. These energy crops are generally classified into two main categories:

- **First generation biomass**: sugar and starch-rich crops (e.g., maize, sugar beet, potato), which provide high methane yields but compete with food production.
- **Second generation biomass**: Cellulosic and lignocellulosic crops (e.g., grasses, clover, miscanthus, switchgrass), which can be grown on marginal land, offering greater sustainability but lower biodegradability due to their lignin content.

Prior to digestion, feedstocks may undergo pre-treatment to enhance hydrolysis and thus improve methane yields. These treatments include particle size reduction (milling, chopping), ensiling, and more advanced methods for lignocellulosic substrates, such as steam explosion, wet oxidation, or alkaline treatments. Such steps improve microbial access to organic compounds, shorten hydraulic retention time, and maximise methane production.

Common feedstocks also include the organic fraction of municipal, commercial, and industrial waste, in addition to first-generation biomass sourced from food or forage crops cultivated for energy purposes.

Applied process: Anaerobic digestion is a biological process in which microorganisms decompose organic matter in the absence of oxygen, producing raw biogas

typically containing 50–70% methane (CH_4) and 30–50% carbon dioxide (CO_2). Upgrading and purification processes can increase the methane content above 95%, yielding biomethane suitable for injection into the natural gas grid.

The overall process can be represented by the simplified reaction:

$$C_6H_{12}O_6 \longrightarrow 3\,CH_4 + 3\,CO_2 \tag{5.2}$$

System boundaries

Feedstock. Anaerobic digestion enables the conversion of a wide range of biomass types into biomethane, with the conversion efficiency being highly dependent on the specific characteristics of the feedstock. In this analysis, we adopt the assumptions proposed by [2], which provide a consistent basis for estimating feedstock requirements. Accordingly, it is assumed that approximately $[3-15]$kg of biomass is needed to produce 1MJ of biomethane. This wide range reflects the variability in moisture content, with wet biomass (e.g., slurry) exhibiting lower energy density and thus requiring higher mass input compared to dry biomass (e.g., energy crops or dry manure).

Biomass land requirement and harvesting process The harvesting phase is limited to the collection of the biomass using a forage harvester. No additional preprocessing steps are considered at this stage.

To estimate the land surface required for the production of 1MJ of biomethane, data on agricultural yield reported by [41] has been used. The yield, expressed in terms of energy output per hectare per year, allows for a direct estimation of the area necessary to support a given level of biomethane production, taking into account the conversion efficiency of the anaerobic digestion process and the energy content of the feedstock. As a result, it is concluded that approximately

$$5.44 \times 10^{-6}\ \text{ha/MJ}$$

of agricultural land is necessary to produce 1 MJ of biomethane when using a mixture of slurry and grass as feedstock.

Transport The transport of biomass from the harvesting site to the anaerobic digester is assumed to cover a distance ranging between 10 and 50km, depending on the availability and location of feedstocks such as slurry and grass.

The transport of biomethane is modelled exclusively via pipeline infrastructure. The transmission distance is assumed to range from 100 to 400km, depending on the spatial distribution of production and demand centers.

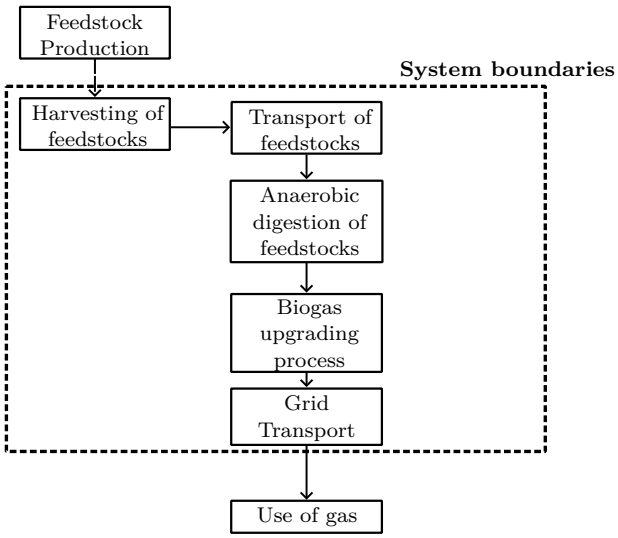


Figure 5.3: Gas transport is assumed to occur predominantly via pipeline.

5.3.2 The syngas pathways

In this conversion pathway, the biomass feedstock first undergoes a drying stage, after which it is subjected to gasification, yielding a synthesis gas (*syngas*) predominantly composed of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4). The resulting syngas stream is subsequently cooled and treated to remove tars and other undesired compounds. Following purification, the gas is pressurised and introduced into a methanation unit, where catalytic reactions transform it into a mixture rich in methane and carbon dioxide. In the final step, the stream is further refined through CO_2 separation, producing a synthetic natural gas (SNG) of a quality suitable for direct injection into the natural gas distribution network.

The same transport conditions, in terms of both distance and mode, as those defined for the biogas pathways have been adopted in this scenario.

Assumption 1: The entire conversion chain, including syngas production, purification, and methanation, is assumed to occur on a single site. This configuration is inspired by integrated demonstration projects such as GoBiGas 20 MW SNG [40]

Assumption 2: Since the biomass used in this process often originates as a by-product or waste stream from another industrial or agricultural process, the biomass harvesting phase is not accounted for within the system boundaries. This differs from the biomethane production process via anaerobic digestion, where harvesting constitutes a distinct and necessary operation.

Feedstock According to the findings reported in [2], the production of 1 MJ of methane requires between 0.11 and 0.80 kg of biomass feedstock, depending on the type and quality of the resource. This range reflects the variability in methane yield associated with different feedstock categories such as municipal solid waste (MSW), agricultural residues, and forestry by-products. Higher-quality substrates, typically with lower moisture content and higher volatile solids, tend to produce more methane per unit of mass, whereas low-quality or highly diluted waste streams exhibit lower conversion efficiency.

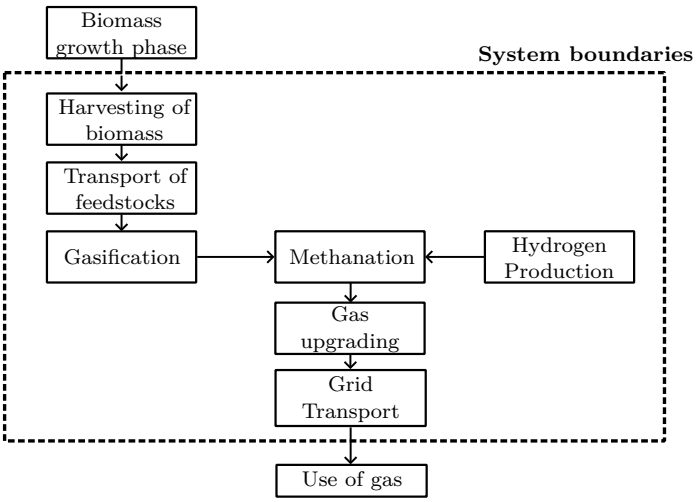


Figure 5.4: Hydrogen production is a key lever in the overall emissions impact.

5.3.3 Power-to-Methane

The power-to-methane pathway relies on the Sabatier methanation reaction, wherein carbon dioxide (CO_2) is combined with hydrogen (H_2) according to the following exothermic reaction:

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O \tag{5.3}$$

This reaction is catalysed by nickel at temperatures ranging from 300 to 400 °C, enabling the valorisation of surplus renewable electricity by converting it into synthetic methane, commonly referred to as e-methane or synthetic CH_4.

Feedstock As will be further detailed in the section addressing electrolytic hydrogen, this pathway is highly dependent on the origin and carbon intensity of

the electricity used, rendering it particularly sensitive to upstream assumptions embedded in the energy system model.

In this analysis, hydrogen is assumed to be exclusively sourced from water electrolysis.

It is worth noting that carbon feedstock production is excluded from the system boundaries. However, the carbon capture process itself is accounted for within the analysis.

System Boundaries

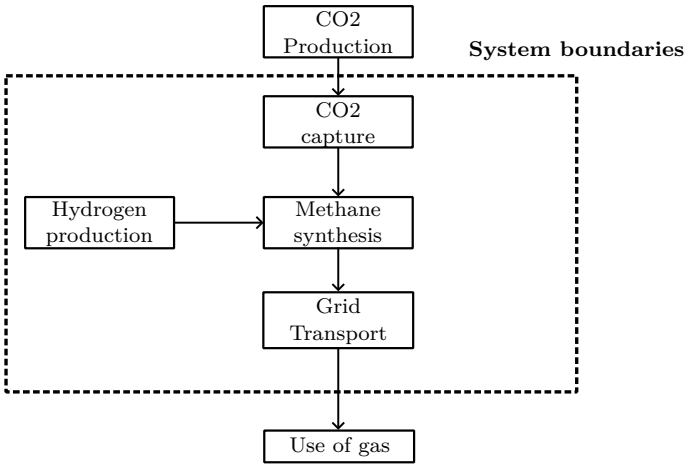


Figure 5.5: The carbon intensity of electricity used for hydrogen production significantly affects the overall result.

5.4 Pathways for renewable hydrogen production

A wide range of hydrogen production technologies currently exists, spanning from fossil fuel-based systems, most notably steam methane reforming (SMR) from natural gas, to renewable energy-based systems such as electrolysis powered by wind or solar energy. Despite their potential, these low-emission technologies remain marginal in global hydrogen production.

In 2023, global hydrogen production amounted to 97 million tonnes, with less than 1 percent derived from low-emission sources. However, projections based on announced industrial projects suggest that low-emissions hydrogen could increase significantly, reaching 49 million tonnes per annum by 2030, up from the 38 million tonnes forecasted in the Global Hydrogen Review 2023 [35].

Current production methods and environmental implications At present, the dominant method for industrial hydrogen production involves fossil-based processes such as catalytic reforming, cracking, and gasification. These pathways, which utilise feedstocks like coal, natural gas, and oil, account for approximately 96% of global hydrogen output [44]. While these resources are abundant and economically accessible, their use is associated with significant environmental drawbacks, including high greenhouse gas emissions and pollutant release.

Bio-Hydrogen Currently, the combined gasification, steam reforming, and pressure swing adsorption (PSA) pathway is considered the most energy-efficient approach for bio-hydrogen production. However, its environmental performance remains suboptimal due to its reliance on non-renewable inputs, particularly within the steam reforming and PSA stages. Enhancing the sustainability of this route necessitates the substitution of fossil-based agents with renewable alternatives, as highlighted in [23].

5.4.1 Electrolytic hydrogen

In the context of climate policy and energy system decarbonisation, this study focuses specifically on the role and impact of renewable hydrogen, i.e., hydrogen produced via electrolysis using electricity generated from renewable sources. The definition and delimitation of what qualifies as "renewable" are central to both regulatory frameworks and scenario-based assessments.

The case of hydrogen produced through electrolysis is particularly noteworthy in the context of decarbonisation strategies. Electrolytic hydrogen is deemed renewable only when the electricity employed in the electrolysis process is itself generated from renewable sources. This condition aligns with the broader objective of reducing the carbon footprint across the energy value chain.

Nonetheless, regulatory frameworks diverge significantly across jurisdictions regarding the classification and subsidisation of hydrogen based on its carbon intensity. In the United States, hydrogen is categorized as low-carbon if its production emits less than 4 $kgCO_2/kg_{H2}$. Conversely, the European Union, through the Renewable Fuels of Non-Biological Origin (RFNBO) classification, currently restricts subsidies to hydrogen that is exclusively produced from renewable electricity,referred to as green hydrogen. However, recent consultations indicate a forthcoming definition for low-carbon hydrogen capped at a carbon intensity of 3.384 $kgCO_2/kg_{H2}$ [32].

While various jurisdictions provide differing thresholds for what constitutes low-carbon or green hydrogen, these often reflect political and economic considerations more than scientifically grounded constraints. To ensure internal methodological

consistency and alignment with climate targets, we define the upper limit of carbon intensity for renewable hydrogen production based on results from the SSP1-PkBudg500 scenario.

System boundaries

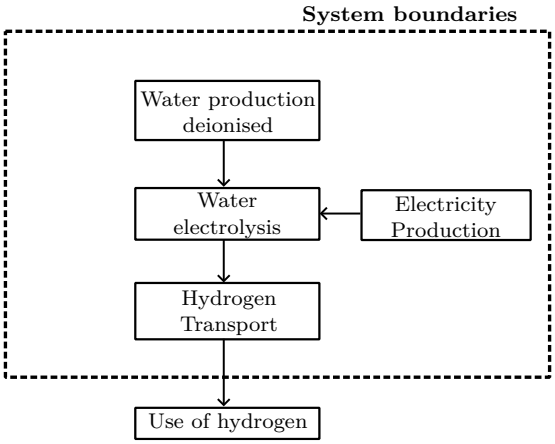


Figure 5.6: Water is assumed to be deionised on-site.

5.4.2 Bio-hydrogen

Hydrogen production from biomass represents a promising alternative to more carbon-intensive methods, such as electrolysis powered by non-renewable electricity. Two main categories of conversion pathways are commonly identified: thermochemical and biochemical routes.

Thermochemical Conversion Pathways

Thermochemical processes include combustion, pyrolysis, gasification, and liquefaction. These methods involve the decomposition of biomass under high temperatures, under varying oxidative conditions. Among these:

- **Pyrolysis** involves heating the biomass in the range of 377°C to 527°C under a pressure of 0.1 to 0.5 MPa, in the absence of air. This process generates a mixture of gases, bio-oil, and char. However, pyrolysis has not yet been fully developed at an industrial scale specifically for hydrogen production.

- **Gasification** is a more mature and widely studied process. It takes place at temperatures exceeding 850°C in a low-oxygen environment. Biomass with a moisture content below 35% can be converted into a synthesis gas (syngas) rich in carbon monoxide and hydrogen. The syngas can then undergo steam reforming to enhance the hydrogen yield.
- **Combustion** may also be integrated in certain configurations, although it is generally less selective for hydrogen production.

All thermochemical routes typically involve an initial thermal pretreatment stage (e.g., drying, partial pyrolysis) to release volatile compounds from the biomass. This is followed by high-temperature reactions, either oxidative or non-oxidative, that produce hydrogen-rich gas mixtures. Hydrogen is then separated and purified from the resulting syngas using downstream processing techniques. The overall hydrogen yield is highly sensitive to operational parameters, including temperature, gasifying agent (e.g., air, steam, or oxygen), biomass properties, and catalyst presence.

According to recent literature, the gasification of biomass residues stands out as one of the most technologically mature thermochemical routes for hydrogen production. This pathway offers the dual advantage of utilizing renewable feedstocks and enabling integration with carbon capture technologies, thereby enhancing its potential for low-emission hydrogen generation [14].

Biochemical Conversion Pathways

Biochemical routes include direct and indirect photolysis, photobiological fermentation, and certain electrochemical processes. These technologies rely on the metabolic capacities of microorganisms or photo-induced reactions to generate hydrogen from organic substrates. However, most of these methods remain at the research and development stage, facing substantial technological barriers.

Biomass to hydrogen via electrolysis

This pathway will not be characterized independently in the present analysis, as it is already encompassed within the broader electrolysis category. Moreover, its environmental impact has been shown to be comparatively lower than other biomass-based hydrogen production methods [23].

System boundaries

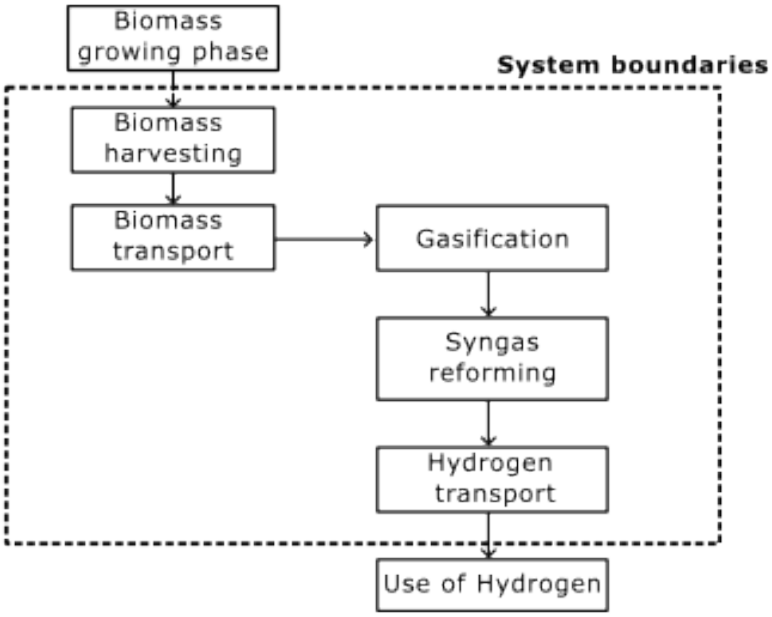


Figure 5.7: The same assumptions as those applied to gas gasification are retained.

5.5 Pathways for renewable ammoniac production

The conversion of molecular dinitrogen (N_2) into ammonia (NH_3) represents one of the most essential chemical transformations. At the industrial level, this transformation is predominantly carried out via the Haber-Bosch process, which involves the direct reaction between atmospheric dinitrogen and dihydrogen (H_2) under high temperature and pressure.

This process currently accounts for the production of approximately 160 million metric tons of ammonia annually, serving agricultural and industrial purposes. However, it remains highly energy-intensive, consuming between 1 and 2 percent of the world's annual primary energy supply [39, 20]. In terms of technological maturity, thermocatalytic ammonia synthesis, with over a century of industrial use, is comparable to petroleum refining and petrochemical sectors [19].

Even when coupled with water electrolysis to produce green hydrogen, the Haber-Bosch process remains energetically inefficient at small scales, requiring approximately 22 kilowatt-hours per kilogram of ammonia, compared to around

8 kilowatt-hours per kilogram at large scale. This inefficiency poses significant limitations for its deployment in developing countries or decentralized contexts [20].

Consequently, the future of ammonia synthesis lies not solely in the decarbonization of the Haber-Bosch process through green hydrogen but also from its miniaturization, energy efficiency improvements and the development of the catalysts that could overcome the techno-economic barriers associated with ammonia-based energy storage. And it is worth noting that the transportation phase of ammonia can account for up to 30% of its total carbon footprint [31].

In this context, small-scale ammonia production units designed for local use, such as an on-site fertilizer production or fuel for agricultural machinery, are increasingly attractive. Nevertheless, the application of the Haber-Bosch process at such scales exacerbates energy consumption, thereby limiting its viability in the absence of substantial technological innovation.

System boundaries

In this section hydrogen production is conducting under the same assumption regarding the origin of electricity as established in Section 5.4.1.

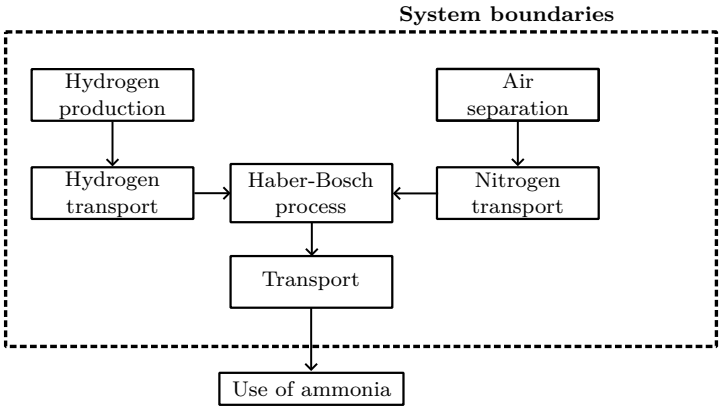


Figure 5.8: Dinitrogen is sourced via air separation.

5.6 Pathways for renewable methanol production

Two principal pathways for the renewable production of methanol are considered in this section. The first involves methanol synthesis from syngas, which is produced via biomass gasification followed by a full-methanol steam reforming process. This

process is optimized to yield a syngas with a hydrogen to carbon monoxide molar ratio of 2.2:1, which is considered ideal for the catalytic synthesis of methanol.

The second pathway, referred to as Power-to-Methanol (PtM), involves the reaction of renewable hydrogen, typically produced via water electrolysis, with a concentrated source of carbon dioxide. In this study, Direct Air Capture (DAC) is assumed as the carbon source. The captured CO_2 is then hydrogenated under appropriate thermodynamic and kinetic conditions to yield methanol.

5.6.1 Biomass to methanol

The most established and scalable pathway for methanol production from biogenic sources is biomass gasification. This process involves the thermal decomposition of solid biomass,such as wood, agricultural residues, or dry organic waste, under high temperatures and a limited supply of oxidising agents(air, oxygen, or steam).

The gasification process yields a synthesis gas (syngas), primarily composed of H_2, CO, and CO_2, which is subsequently purified and catalytically converted into methanol. The catalytic synthesis step is technologically analogous to conventional methanol production routes based on natural gas.

This pathway is particularly suitable for large-scale applications due to its ability to generate a syngas mixture with an appropriate H_2/CO ratio for downstream catalytic conversion.

Alternative pathways, which are less mature or currently under research and development, include the reforming of biogas, originating from anaerobic digestion. In this route, methane (CH_4) is reformed with steam to produce syngas, which can then be synthesised into methanol via catalytic processes.

System boundaries

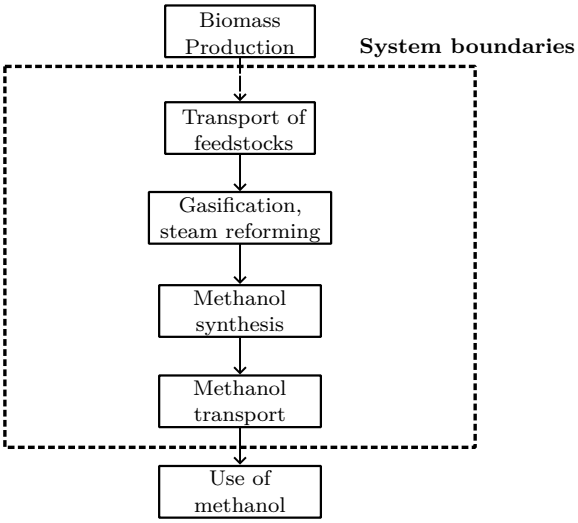


Figure 5.9: The same assumptions as those applied to gas gasification are retained.

5.6.2 Power to methanol

Hydrogen production

The production of hydrogen is accounted for within the boundaries of the prospective life cycle inventory. The same assumptions regarding the origin of electricity for hydrogen production are applied consistently throughout the analysis; for further details, refer to Section 5.4.1.

Carbon Source

In this study, the carbon required for synthetic fuel production is assumed to be supplied via Direct Air Capture (DAC). The selected configuration corresponds to a solvent-based DAC system with an annual capture capacity of 1 $MtCO_2$ and a design lifetime of 20 years, consistent with the Ecoinvent dataset and the techno-economic parameters reported by Qiu *et al.* [33]. The heat demand of the DAC unit is met using a heat pump operating with a coefficient of performance (COP) of 2.9.

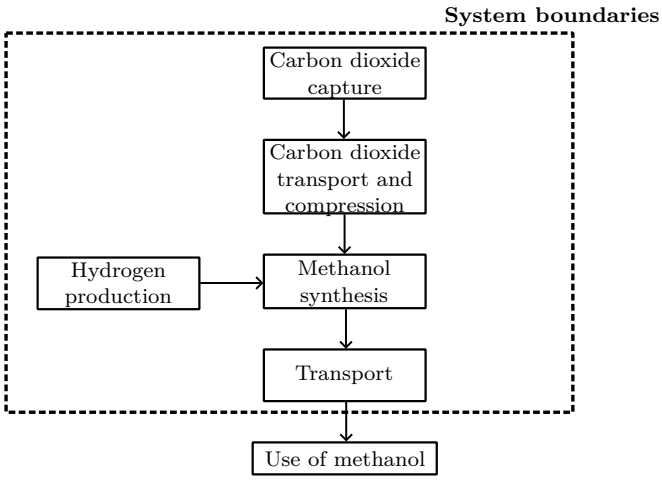


Figure 5.10: Hydrogen significantly influences the final LCA outcome.

5.7 Pathways for renewable Biodiesel production

Multiple technological pathways can be explored for the production of biodiesel. Historically, methods such as pyrolysis, micro-emulsification, and thermal cracking have been investigated for this purpose. Nevertheless, these approaches have been excluded from large-scale practical applications, as they tend to decrease engine efficiency, compromise fuel stability, and yield a product with a lower heating value, ultimately leading to reduced biodiesel output. Consequently, they are not considered viable options for industrial-scale deployment.

In contrast, esterification, inter-esterification, and transesterification have demonstrated the ability to produce biodiesel with both high yield and high quality, meeting established fuel standards. Among these, transesterification is widely regarded as the most effective and reliable method for biodiesel production [27].

Several technological routes exist for carrying out transesterification, including: (i) base-catalyzed transesterification, (ii) acid-catalyzed transesterification, (iii) enzymatic catalysis using lipases, (iv) the use of supercritical alcohols, and (v) esterification/transesterification under supercritical conditions or with heterogeneous catalysts [28].

Currently, base-catalyzed transesterification remains the most common and economically viable method for industrial production. The alternative pathways, acid-catalyzed, enzymatic, and supercritical, hold significant promise for specific feedstocks or niche applications, but they still require further technical or economic improvements to become competitive at a large scale [28].

Usually, methanol is the preferred alcohol for producing biodiesel because of its low cost. [24]

5.7.1 Biomass feedstock

There are three categories of biomass candidates for transesterification:

First-Generation Pathway

This production pathway utilises feedstocks with a high triglyceride content, cultivated specifically for energy purposes, such as rapeseed, soybean, or sunflower. The industrial process generally comprises oil extraction, either through mechanical pressing or solvent-based methods, followed by a transesterification reaction with methanol, yielding biodiesel.

Second-Generation Pathway

This route employs non-food raw materials and residual resources, including used cooking oils and animal fats. A preliminary pre-treatment step is required to remove contaminants and to lower the concentration of free fatty acids. Once conditioned, the feedstock undergoes transesterification to produce biodiesel.

Third-Generation Pathway

This pathway is based on the exploitation of microalgae with a high capacity for lipid accumulation. The process encompasses the cultivation of these microorganisms, extraction of their oil content, and subsequent transesterification to obtain biodiesel.

5.7.2 System boundaries

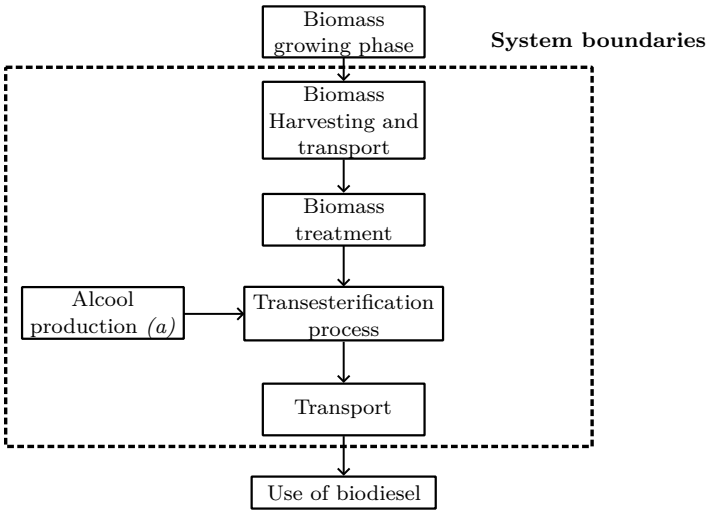


Figure 5.11: The process flow is similar across the three biodiesel production pathways, though their environmental impacts differ.

5.8 Pathways for renewable Bioethanol production

The production process of ethanol is intrinsically dependent on the nature of the raw materials employed. In general, ethanol manufacturing can be decomposed into three principal stages[42].:

1. Extraction of a solution containing fermentable sugars from the selected biomass;
2. Bioconversion of these sugars into ethanol via fermentation;
3. Separation and purification of ethanol, most commonly through a sequence of distillation, rectification, and dehydration operations.

Fermentation-based ethanol synthesis can be conducted using any substrate containing simple or complex sugars as its primary carbohydrate source [26].

First generation biomass

Sucrose-based feedstocks, such as sugarcane, sugar beet or sweet sorghum, are processed through direct juice extraction followed by fermentation. This route

generates by-products like bagasse, which is commonly used for energy production, and vinasse, often applied as a fertiliser. The main advantages are high ethanol yields and low conversion costs, although the process is constrained by seasonal feedstock availability and competition with food production.

Starch-based feedstocks, including maize, wheat and cassava, require enzymatic hydrolysis before fermentation. The process involves liquefaction using α-amylase followed by saccharification with gluco-amylase to produce glucose. [21]

Second generation biomass

Second-generation bioethanol production uses agricultural and forestry residues as well as dedicated energy crops. These feedstocks consist mainly of cellulose, hemicellulose and lignin.

The biochemical route, or sugar platform, begins with a pre-treatment step (such as steam explosion, dilute acid, ammonia fibre expansion) to render cellulose accessible. This is followed by enzymatic hydrolysis using cellulases and hemicellulases to produce a mixture of hexose and pentose sugars, which are then fermented into ethanol.[11]

The thermochemical route, or syngas platform, involves gasifying the biomass to produce synthesis gas composed mainly of CO, H_2, CO_2 and CH_4. This syngas can be converted into ethanol and other products either catalytically, for instance via a modified Fischer–Tropsch process, or biologically, using microorganisms such as *Clostridium ljungdahlii* or *C. autoethanogenum*.[11] This pathway offers the advantage of using the entire biomass, including lignin, but faces challenges such as syngas purification and optimisation of conversion yields.

5.8.1 System boundaries

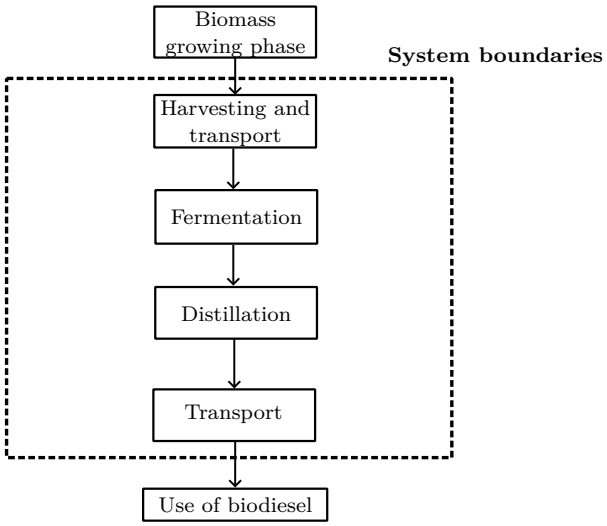


Figure 5.12: It should be noted that if sugar materials such as molasses and sugarcane juice are used for fermentation, then processes like milling, pretreatment, hydrolysis, and detoxification are not necessary.

5.9 Quantitative results and comparative analysis

Table 5.2: Operational global warming potential of resources obtained by pLCA and comparison with non renewable equivalent in ESTD

Resource	**Pathway**	gwp_{op} [ktCO$_2$-eq/GWh] SSP1-PkBudg500	gwp_{op} [ktCO$_2$-eq/GWh] SSP5-Base	gwp_{op} [ktCO$_2$-eq/GWh] not RE
Methane				
	Bio-methane (from biogas)	0.014	0.110	0.2666
	Bio-methane (from syngas)	0.018	0.050	
	Electro-methane (from methanation)	0.0009	0.263	
Hydrogen				
	Hydrogen electrolytic	0.0085	0.196	0.336
	Bio-hydrogen (from syngas)	0.0215	0.053	
Ammonia				
	Ammonia (from Haber-Bosch)	0.014	0.2786	0.285
Methanol				
	Bio-methanol (from syngas)	0.014	0.038	0.35
	Electro-methanol (Power-to-Methanol)	0.0005	0.272	
Biodiesel				
	First Generation	0.036	0.069	0.315
	Second generation	0.003	0.004	
	Third generation	0.031	0.093	
Bioethanol				
	First Generation	0.034	0.066	0.3448
	Second generation	0.028	0.045	

5.9.1 Interpretation

Electro-fuels Hydrogen production exhibits strong carbon competitiveness under the SSP1 scenario. In a world characterised by a highly decarbonised electricity mix, electro-based production pathways, such as electro-methane and electro-methanol, demonstrate exceptional environmental performance. In this context, their life cycle impacts are up to twenty times lower than those of biomass-based alternatives evaluated under the same SSP1 framework.

Nevertheless, the environmental performance of electro-based (ammonia also included, as it is synthesised via the Haber–Bosch process.) routes is highly sensitive to the carbon intensity of the electricity used for water electrolysis. Under the SSP5 scenario, where the power mix remains carbon-intensive, the carbon footprint of hydrogen increases substantially, by a factor of 23 compared to its SSP1 counterpart.

As a result, electro-methane and electro-methanol production under SSP5 are respectively 300 to 540 times more carbon-intensive than under SSP1, highlighting

the critical influence of upstream electricity sourcing on the overall life cycle performance of electrochemical fuel pathways.

While electricity remains the primary driver of carbon intensity for electro-based routes, it is not the sole contributor to the environmental footprint. For biomass-based pathways, additional significant impacts arise from the transportation of biomass feedstock and from various intermediate processing steps, as described in the respective production chains above.

Electro-fuels derived from the SSP5 scenario ultimately exhibit environmental impacts comparable to those of their fossil-based counterparts. This raises fundamental questions regarding the classification of electro-fuels as "renewable," particularly when the electricity used for electrolysis originates from a carbon-intensive mix.

These findings suggest that in a world failing to achieve decarbonisation, electro-based fuel pathways, when supplied by an average or fossil-dominated electricity mix, offer limited advantages over conventional fossil fuel routes from a life cycle perspective.

Bio-fuels Biomass-derived fuels under the SSP1 scenario exhibit life cycle impacts that are approximately 14 to 25 times lower than those of their non renewable counterparts.

When comparing biomass-based fuels across scenarios, SSP1 generally yields two to three times lower environmental impacts than SSP5 for equivalent pathways. An exception to this trend is methane produced via anaerobic digestion of biogas, which proves to be ten times more favourable under SSP1 compared to SSP5.

Despite this sensitivity to scenario assumptions, renewable fuel pathways consistently outperform fossil-based ones. Even in the least favourable case, methane from biogas, the SSP5 variant remains at least twice as advantageous, while in the most favourable case, biomethanol from syngas, SSP5 offers a ninefold reduction in impact relative to non-renewable alternatives.

Chapter 6

Conclusion

Energy system models are powerful tools for designing strategic pathways toward the decarbonisation of our societies. Among such tools, the model developed by Limpens et al. [25] and Moret et al. [30] offers a comprehensive representation of the energy system, explicitly accounting for intersectoral interactions and synergies.

The greater the accuracy and relevance of these models, especially when they reflect the societal trends and long-term constraints, the more informative and plausible the resulting energy scenarios become. EnergyScope, while fundamentally deterministic, is specifically designed to be compatible with sensitivity analyses, thanks to its relatively low computational burden.

This master's thesis has aimed to address two key limitations of the EnergyScope model in its current formulation:

- The implementation of a more realistic estimation of the life cycle carbon impact of renewable fuels.
- The integration of Shared Socioeconomic Pathways (SSPs) to refine long-term parameter assumptions, with a focus on the year 2050.

Through these two modelling enhancements, this research sought to answer the following questions:

- How does the integration of life cycle carbon impacts of renewable fuels alter the model energy system optimum for Belgium by 2050 ?
- What would constitute a more accurate estimation of the carbon impact associated with renewable fuels imported into Belgium in 2050?

Key findings and conclusions

- This thesis has explored the implications of incorporating non-zero operational carbon impact parameters for renewable fuels into the EnergyScope model. The results show that such integration has a significant influence on both the import mix and the technology choices computed by the optimisation.

  Specifically, increasing the operational carbon impact of renewable fuels, while keeping it below that of their fossil-based equivalents, often leads the model to favour an increased share of renewable gas imports. This behaviour was observed consistently across multiple sensitivity analyses: as the carbon intensity of renewable resources was incrementally increased, the model progressively substituted other imports with renewable gas in order to maintain a constrained system-wide carbon budget.

  Once this substitution potential is exhausted, the model responds by switching to alternative technologies or resources to meet a given end-use demand (EUD). This highlights the model's adaptive optimisation capability in the face of tighter emission constraints.

  Furthermore, the model exhibits high sensitivity to small variations in the relative operational carbon impacts between two resources capable of serving the same demand. Even minor differences in these parameters can lead to radical shifts in the selected technology pathway. For instance, two resources with comparable costs but slightly different carbon intensities can cause the model to entirely replace one pathway with another.

  These findings underscore the importance of accurately characterising the carbon impacts of renewable fuels. The assumption that renewable options are carbon-neutral can significantly misguide optimisation outcomes and policy recommendations. Therefore, integrating realistic carbon impact values, even if relatively low, is essential for robust energy system planning.

- The integration of non-zero operational emissions for renewable fuels does not affect the main electricity generation pathways, such as solar, wind, and nuclear.

- The operational carbon impact values of renewable fuels derived through pLCA fall within the range where the model exhibits structural reconfigurations. The performed sensitivity analyses demonstrated that these shifts occur but when specific ratios of operational carbon impacts between competing resources are reached. These thresholds often led to relatively deep systemic changes within the model configuration.

  As a result, even when relying on more precise estimations of the operational carbon impacts of renewable fuels, it remains inherently difficult to anticipate

the model's final configuration. Nonetheless, this master thesis has highlighted the main consequences of integrating operational carbon impacts of renewable fuels into the model's optimal energy scenario.

- The production pathways for renewable fuels are diverse and lead to a wide range of carbon impacts, even for the same final energy carrier. Aggregating these pathways into a single operational carbon equivalent obscures the model's ability to differentiate between them. As a result, nuanced trade-offs between production routes are lost, potentially oversimplifying optimisation outcomes.

- Ultimately, Belgium's ability to achieve carbon neutrality is strongly influenced by the carbon intensity of the renewable fuels it imports. These carbon impacts, in turn, are dependent on the extent to which the exporting regions themselves succeed in decarbonising their own energy systems. This finding reinforces the need to consider the energy system as an interconnected whole, rather than as a collection of isolated national efforts.

Appendix A

Reference scenario data

A.1 Reference scenario data

A.1.1 Resources utilisation

Table A.1: Resource use and potential

Name	Used [GWh/y]	Potential [GWh/y]
METHANOL_RE	54 784.31	∞
RES_SOLAR	61 259.67	∞
RES_WIND	42 540.63	∞
WET_BIOMASS	38 900.00	38 900.00
URANIUM	37 188.95	∞
ELECTRICITY	32 439.87	32 439.87
GAS	24 186.01	∞
WOOD	23 400.00	23 400.00
AMMONIA_RE	23 250.72	∞
H2_RE	15 573.26	∞
WASTE	17 799.99	17 800.00
GAS_RE	9 079.30	∞
BIODIESEL	2 735.31	∞
RES_HYDRO	480.63	∞
ELEC_EXPORT	263.19	∞
COAL	0.075670	33 355.00
LFO	0.054110	∞
DIESEL	0.015166	∞
BIOETHANOL	0.015020	∞
GASOLINE	0.006427	∞
H2	0.00	∞
AMMONIA	0.0	∞
METHANOL	0.0	∞

A.1.2 Technologies installed capacities

Table A.2: End-use and infrastructure capacities

Technology	F **[GW or GWh]**
CAR_BEV	176.96
TRUCK_FUEL_CELL	51.47
PV	59.17
IND_DIRECT_ELEC	20.30
DEC_HP_ELEC	18.59
TRAIN_PUB	16.52
TRAMWAY_TROLLEY	7.96
TRAIN_FREIGHT	7.73
DHN_HP_ELEC	7.61
BUS_COACH_CNG_STOICH	6.13
WIND_ONSHORE	10.00
WIND_OFFSHORE	6.00
METHANOL_TO_HVC	4.89
IND_BOILER_WOOD	2.98
IND_COGEN_GAS	2.97
IND_BOILER_WASTE	2.15
BIO_HYDROLYSIS	2.21
NUCLEAR	2.00
CCGT_AMMONIA	1.18
IND_BOILER_GAS	0.13
HYDRO_RIVER	0.12
BOAT_FREIGHT_DIESEL	27.83

A.2 Non nuclear scenario data

A.2.1 Sankey of non nuclear scenario

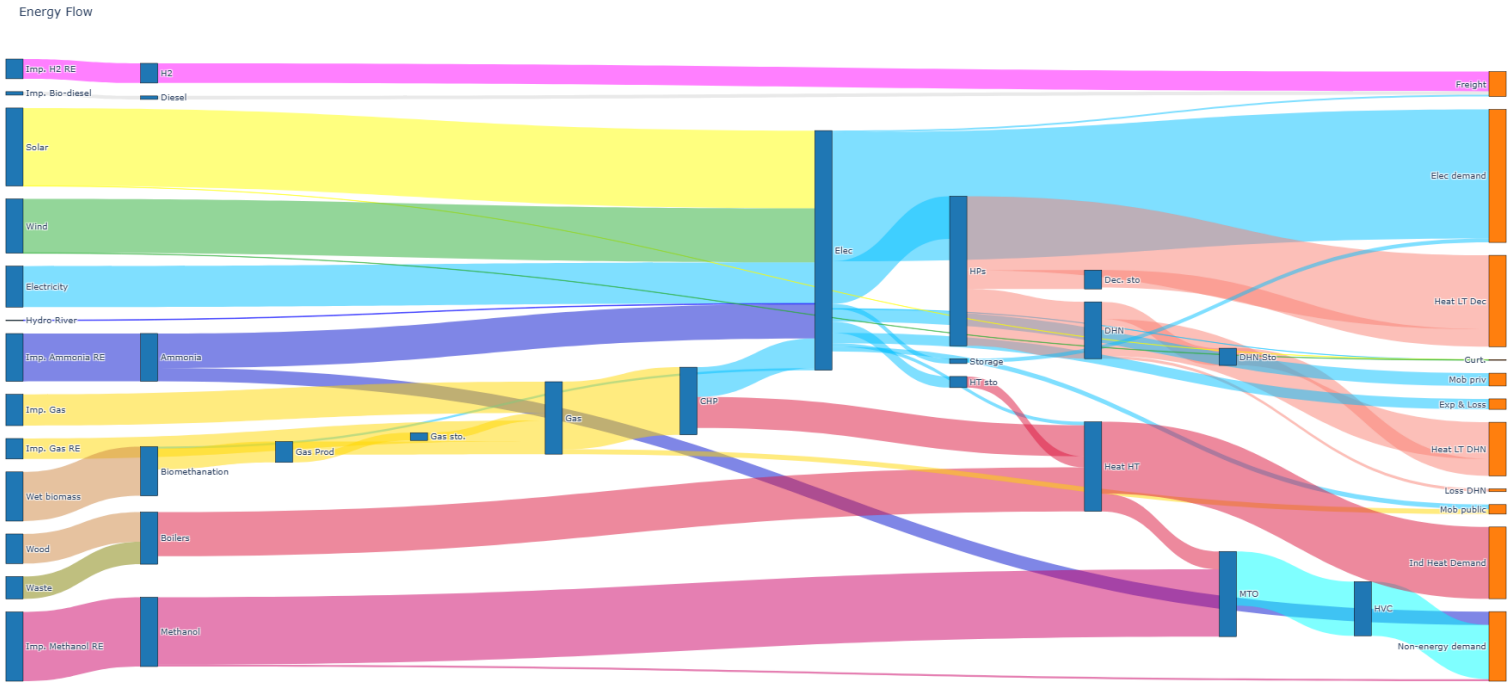


Figure A.1: Sankey diagram of the reference scenario for Belgium in 2050.

A.2.2 Technologies installed capacities

Table A.3: Installed Capacities-

Technology	F **[GW or GWh]**
GAS_STORAGE	9107.35
TS_DHN_SEASONAL	937.05
CAR_BEV	176.96
BEV_BATT	175.56
TS_HIGH_TEMP	71.81
TS_DEC_HP_ELEC	59.53
PV	59.17
TRUCK_FUEL_CELL	51.47
BOAT_FREIGHT_DIESEL	27.83
DEC_HP_ELEC	18.59
IND_DIRECT_ELEC	18.19
TRAIN_PUB	16.52
BATT_LI	13.64
WIND_ONSHORE	10.00
TRAMWAY_TROLLEY	7.96
TRAIN_FREIGHT	7.73
DHN	7.58
DHN_HP_ELEC	7.58
PHS	6.50
BUS_COACH_CNG_STOICH	6.13
WIND_OFFSHORE	6.00
METHANOL_TO_HVC	4.89
IND_COGEN_GAS	3.38
IND_BOILER_WOOD	3.09
CCGT_AMMONIA	2.53
IND_BOILER_WASTE	2.23
BIO_HYDROLYSIS	2.21
LFO_STORAGE	1.64
METHANOL_STORAGE	1.57
DIESEL_STORAGE	1.57
GASOLINE_STORAGE	1.56
AMMONIA_STORAGE	1.54
GRID	1.37
EFFICIENCY	0.99
HYDRO_RIVER	0.12

A.2.3 Resources use and potential

Table A.4: Resource Use and Potential in the Energy System

Name	Used [GWh/y]	Potential [GWh/y]
ELECTRICITY	32 439.87	32 439.87
GASOLINE	0.00086	∞
DIESEL	0.00208	∞
BIOETHANOL	0.00198	∞
BIODIESEL	2 735.32	∞
LFO	0.00780	∞
GAS	24 730.21	∞
GAS_RE	16 186.39	∞
WOOD	23 400.00	23 400.00
WET_BIOMASS	38 900.00	38 900.00
COAL	0.01011	33 355.00
URANIUM	0.00000	∞
WASTE	17 800.00	17 800.00
H2	0.00001	∞
H2_RE	15 573.20	∞
AMMONIA	0.00000	∞
METHANOL	0.00000	∞
AMMONIA_RE	37 861.34	∞
METHANOL_RE	54 784.34	∞
ELEC_EXPORT	126.80	∞
CO2_EMISSIONS	36 319.35	∞
RES_WIND	42 713.80	∞
RES_SOLAR	61 389.92	∞
RES_HYDRO	480.75	∞
RES_GEO	0.00000	∞
CO2_ATM	0.00041	∞
CO2_INDUSTRY	0.00000	0.00
CO2_CAPTURED	0.00000	0.00

Appendix B

pLCA Inventory: Ecoinvent activities

B.1 Inventories

B.1.1 Methane production pathways inventories

Inventory of the biogas pathways

This inventory outlines the main inputs required to produce 1 MJ of CH_4 via the biogas pathway. The production quantities for intrant et transport are based on anaerobic digestion scenario from the work of [41]. For quantities conversion [2]

Table B.1: Biomass feedstock requirement for 1 MJ of biomethane

Input	**Amount (kg/MJ)**	Ref.
Biomass	[3 - 15]	[2]

LA masse de biomasse nécessaire dépend du moisture content.

Table B.2: Ecoinvent activities

Product	**Activity**
Biomethane from biogas	biomethane production, from biogas upgrading, using amine scrubbing
Biomass transport	market for transport, freight, lorry 16–32 metric ton, EURO6
Methane transport	market for transport, pipeline, long distance, natural gas

Table B.3: Biomethane production activity

Product	**Activity**
Activated silica	activated silica production
Activated carbon, granular	market for activated carbon, granular
Chemical factory, organics	market for chemical factory, organics
Monoethanolamine	market for monoethanolamine
Water, deionised	market for water, deionised
Electricity, medium voltage	market group for electricity, medium voltage
2 wt-% potassium iodide solution	production of 2 wt-% potassium iodide solution
Biogas	treatment of sewage sludge by anaerobic digestion

Inventory of the gasification process

Table B.4: Ecoinvent activities

Product	**Activity**
Biomethane, high pressure	biomethane production, high pressure from synthetic gas, wood, fluidised technology
Transport, pipeline, long distance, natural gas	market for transport, pipeline, long distance, natural gas
Transport, freight, sea, tanker for liquefied natural gas	market for transport, freight, sea, tanker for liquefied natural gas
Transport, freight, lorry 16–32 metric ton, EURO6	market for transport, freight, lorry 16–32 metric ton, EURO6

Table B.5: Biomethane production Ecoinvent activity

Product	Activity
Aluminium oxide, non-metallurgical	market for aluminium oxide, non-metallurgical
Charcoal	market for charcoal
Dolomite	market for dolomite
Fatty acid methyl ester	esterification of rape oil
Heat, central or small-scale, other than natural gas	market for heat, central or small-scale, other than natural gas
Industrial furnace, natural gas	market for industrial furnace, natural gas
Inert waste	market for inert waste
Nickel, class 1	market for nickel, class 1
Silica sand	market for silica sand
Sodium hydroxide, without water, in 50% solution state	market for sodium hydroxide, without water, in 50% solution state
Sulfuric acid	market for sulfuric acid
Synthetic gas factory	market for synthetic gas factory
Tap water	market for tap water
Waste mineral oil	market for waste mineral oil
Waste zeolite	market for waste zeolite
Wastewater, average	market for wastewater, average
Wood ash mixture, pure	market for wood ash mixture, pure
Wood chips, dry, measured as dry mass	market for wood chips, dry, measured as dry mass
Wood chips, wet, measured as dry mass	market for wood chips, wet, measured as dry mass
Zeolite, powder	market for zeolite, powder
Zinc	market for zinc
Electricity, low voltage	market for electricity, low voltage
Electricity, medium voltage	market for electricity, medium voltage
Electricity, low voltage	market group for electricity, low voltage
Electricity, medium voltage	market group for electricity, medium voltage

Power to methane process

Données tirées de [34] pour la production du

Table B.6: Ecoinvent activities

Product	Activity
Transport, pipeline, long distance, natural gas	market for transport, pipeline, long distance, natural gas
Transport, freight, sea, tanker for liquefied natural gas	market for transport, freight, sea, tanker for liquefied natural gas
Methane, from electrochemical methanation	methane, from electrochemical methanation, with carbon from atmosphere, using heat pump heat

Table B.7: Methane from methanation Ecoinvent activity

Product	Activity
Sabatier reaction methanation unit	sabatier reaction methanation unit construction
Nickel-based catalyst for methanation	production of nickel-based catalyst for methanation
Carbon dioxide, captured from atmosphere	carbon dioxide, captured from atmosphere, with a solvent-based direct air capture system, 1MtCO_2, with heat pump heat, and grid electricity
Hydrogen, gaseous, 30 bar	hydrogen production, gaseous, 30 bar, from PEM electrolysis, from grid electricity

B.1.2 Hydrogen production pathways inventories

Electrolytic hydrogen

Table B.8: Electrolyzer and fuel cell activities

Product	Activity
Electrolyzer, 1MWe, PEM, Balance of Plant	electrolyzer production, 1MWe, PEM, Balance of Plant
Electrolyzer, 1MWe, PEM, Stack	electrolyzer production, 1MWe, PEM, Stack
Water, deionised	market for water, deionised
Electricity, low voltage	market group for electricity, low voltage
Used fuel cell balance of plant, 1MWe, PEM	treatment of fuel cell balance of plant, 1MWe, PEM
Used fuel cell stack, 1MWe, PEM	treatment of fuel cell stack, 1MWe, PEM

Bio-hydrogen

Table B.9: Ecoinvent activities for bio-hydrogen

Product	Activity
Syngas, from biomass gasification	syngas, from biomass gasification
Chemical factory, organics	market for chemical factory, organics
Liquid storage tank, chemicals, organics	market for liquid storage tank, chemicals, organics
Steam, in chemical industry	market for steam, in chemical industry
Electricity, medium voltage	market group for electricity, medium voltage

B.1.3 Ammonia production pathways inventories

Table B.10: Ammonia-related activities (duplicates removed)

Product	Activity
Ammonia synthesis catalyst	ammonia synthesis catalyst production
Chemical factory, organics	market for chemical factory, organics
Nitrogen, liquid	market for nitrogen, liquid
Inert waste, for final disposal	treatment of inert waste, inert material landfill
Transport, freight train	market for transport, freight train
Transport, freight, inland waterways, barge	market for transport, freight, inland waterways, barge
Transport, freight, lorry, unspecified	market for transport, freight, lorry, unspecified
Transport, freight, sea, container ship	market for transport, freight, sea, container ship
Hydrogen, gaseous, 30 bar	hydrogen production, gaseous, 30 bar, from PEM electrolysis, from grid electricity
Electricity, high voltage	market group for electricity, high voltage

B.1.4 Methanol production pathways inventories

Bio-methanol

Table B.11: Ecoinvent activities for bio-methanol

Product	Activity
Aluminium oxide, non-metallurgical	market for aluminium oxide, non-metallurgical
Copper oxide	market for copper oxide
Methanol factory	market for methanol factory
Molybdenum	market for molybdenum
Nickel, class 1	market for nickel, class 1
Synthetic gas	market for synthetic gas
Wastewater, average	market for wastewater, average
Water, deionised	market for water, deionised
Zinc	market for zinc
Electricity, medium voltage	market for electricity, medium voltage
Electricity, medium voltage	market group for electricity, medium voltage

Power-to-methanol

Table B.12: Ecoinvent activities for Power-to-Methanol

Product	Activity
Methanol production facility, construction	methanol production facility, construction
Methanol, unpurified	methanol synthesis, hydrogen from electrolysis, CO_2 from DAC
Heat, from steam, in chemical industry	steam production, as energy carrier, in chemical industry

Table B.13: Ecoinvent activities for unpurified methanol

Product	Activity
Aluminium oxide, metallurgical	market for aluminium oxide, metallurgical
Carbon dioxide, captured from atmosphere	carbon dioxide, captured from atmosphere, with a solvent-based direct air capture system, 1MtCO_2, with heat pump heat, and grid electricity
Copper oxide	market for copper oxide
Electricity, low voltage	market group for electricity, low voltage
Hydrogen, gaseous, 30 bar	hydrogen production, gaseous, 30 bar, from PEM electrolysis, from grid electricity
Methanol production facility, construction	methanol production facility, construction
Tap water	market for tap water
Wastewater, average	treatment of wastewater, average, wastewater treatment
Zinc oxide	market for zinc oxide

B.1.5 Biodiesel production pathways inventories

Biodiesel from first generation biomass

Table B.14: Ecoinvent activities for biodiesel from first generation biomass

Product	Activity
Electricity, medium voltage	market group for electricity, medium voltage
Heat, from steam, in chemical industry	market for heat, from steam, in chemical industry
Hydrochloric acid, without water, in 30% solution state	market for hydrochloric acid, without water, in 30% solution state
Methanol	market for methanol
Refining of crude vegetable oil from rapeseed	refining of crude vegetable oil from rapeseed
Sodium methoxide	market for sodium methoxide
Transport, freight train	market for transport, freight train
Transport, freight, inland waterways, barge	market for transport, freight, inland waterways, barge
Transport, freight, lorry, unspecified	market for transport, freight, lorry, unspecified
Transport, freight, sea, tanker for petroleum	market for transport, freight, sea, tanker for petroleum
Transport, pipeline, onshore, petroleum	market for transport, pipeline, onshore, petroleum

Biodiesel from second generation biomass

Table B.15: Ecoinvent activities for biodiesel from second generation biomass

Product	Activity
Electricity, medium voltage	market group for electricity, medium voltage
Methanol	market for methanol
Natural gas, medium pressure, vehicle grade	market for natural gas, medium pressure, vehicle grade
Phosphoric acid, industrial grade, without water, in 85% solution state	market for phosphoric acid, industrial grade, without water, in 85% solution state
Potassium hydroxide	market for potassium hydroxide
Potassium sulfate	market for potassium sulfate
Transport, freight train	market for transport, freight train
Transport, freight, inland waterways, barge	market for transport, freight, inland waterways, barge
Transport, freight, lorry, unspecified	market for transport, freight, lorry, unspecified
Transport, freight, sea, tanker for petroleum	market for transport, freight, sea, tanker for petroleum
Waste cooking oil	supply and refining of waste cooking oil

Biodiesel from third generation biomass

Table B.16: Ecoinvent activities for biodiesel from third generation biomass

Product	Activity
Algae harvesting for dry algae production	farming and supply of dry algae
Electricity, medium voltage	market group for electricity, medium voltage
Ethanol, without water, in 99.7% solution state, from ethylene	market for ethanol, without water, in 99.7% solution state, from ethylene
Heat, from steam, in chemical industry	market for heat, from steam, in chemical industry
Hexane	market for hexane
Methanol	market for methanol
Sodium hydroxide, without water, in 50% solution state	market for sodium hydroxide, without water, in 50% solution state
Sulfuric acid	market for sulfuric acid
Water, completely softened	market for water, completely softened

B.1.6 Bioethanol production pathways inventories

Bioethanol from first generation biomass

Table B.17: Ecoinvent activities for bioethanol from first generation biomass

Product	Activity
Electricity, medium voltage	market group for electricity, medium voltage
Heat, from steam, in chemical industry	market for heat, from steam, in chemical industry
Sugar beet cultivation	farming and supply of sugarbeet
Transport, freight train	market for transport, freight train
Transport, freight, inland waterways, barge	market for transport, freight, inland waterways, barge
Transport, freight, lorry, unspecified	market for transport, freight, lorry, unspecified
Transport, freight, sea, tanker for petroleum	market for transport, freight, sea, tanker for petroleum

Bioethanol from second generation biomass

Table B.18: Ecoinvent activities for bioethanol from second generation biomass

Product	Activity
Ammonia, anhydrous, liquid	market for ammonia, anhydrous, liquid
Construction work, heat and power co-generation unit, 160kW electrical	construction work, heat and power co-generation unit, 160kW electrical
Diammonium phosphate	market for diammonium phosphate
Enzymes	market for enzymes
Ethanol fermentation plant	market for ethanol fermentation plant
Forest residue	supply of forest residue
Glucose	market for glucose
Quicklime, milled, packed	market for quicklime, milled, packed
Sodium hydroxide, without water, in 50% solution state	market for sodium hydroxide, without water, in 50% solution state
Sulfuric acid	market for sulfuric acid
Tap water	market for tap water

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