DEPARTMENT OF ENGINEERING MANAGEMENT

Navigating Uncertainties for Ensuring Energy Security

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RESEARCH PAPER 2024-001
MARCH 2024

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D/2024/1169/001

Navigating Uncertainties for Ensuring Energy Security

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Abstract

The expansion of generation capacity in Europe is witnessing substantial growth, primarily driven by the adoption of clean energy sources that are poised to transform global electricity systems. However, the rapid growth in capacity presents challenges due to the variable and uncontrollable nature of renewable energy, leading to a less predictable and more uncertain energy supply. This paper will focus on the issue of supply security and simulation various scenarios for Belgium's future energy mix, using the urbs software, which is a linear programming model specifically tailored to handle complex energy systems, considering both total system cost and total emitted CO_2 of the energy landscape. The investigation of planned actions reveals the risks of blackouts, primarily due to the lower baseload capacity of nuclear energy and the increasing share of renewable energy sources in Belgium and neighboring countries. The results highlight the crucial relationship between cross-border capacity capacity, storage capacity, CO_2 emissions, and costs. It underscores the importance of proactive planning and investment in cross border capacity and storage infrastructure to enhance the resilience and decarbonization of energy systems. By optimizing the utilization of renewable energy sources and minimizing environmental impacts, the findings contribute to the ongoing transition towards a sustainable and secure energy supply.

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Introduction

Belgium's central geographical position within Europe, combined with its strong electricity and natural gas infrastructure, and well-developed port facilities for oil and gas trading, make it an important player in the European energy system. The country places a priority on international collaboration concerning energy and is a dynamic participant in various international institutions focused on energy markets and security [47].

Belgium's energy mix has a historical reliance on nuclear power. Despite the permanent closure of the nuclear power plant Doel 3 at the end of September 2022, the nuclear production park exhibited a high level of availability. Nuclear energy accounted for 47.3% of the total electricity mix, with a total production of 41.8 TWh. The increased availability of the nuclear production park had a negative impact on electricity production from gas. Nevertheless, gas still contributed significantly to the energy mix in 2022, generating 23.2 TWh, which corresponds to 26.9% of the mix. The production of wind and solar energy increased to 17.4 TWh, compared to 15.2 TWh in 2021. This rise is mainly due to the gradual expansion of installed production capacity for onshore wind (+14%) and solar energy (+35%). The production of offshore wind energy remained stable and is expected to increase only from 2027-2028 onwards [10, 13, 22, 23, 34, 42]. With the growing share of variable renewable energy sources in Europe, the need for intercountry energy exchange is also increasing. International exchanges and exports continue to be high. This trend is clearly ongoing, and Belgium remains a net exporter (with 6.6 TWh of net exports in 2022). In total, the country exported 22.2 TWh of electricity, which represents a slight decrease compared to the exports in 2021 (22.8 TWh). Due to the increase in renewable production capacity and the high availability of traditional production parks, there was often an excess of electricity in 2022 that was exported to neighboring countries [34].

Belgium's energy policy is primarily focused on a shift towards a low-carbon economy, while ensuring supply security, lowering costs for end-users, fostering market competition, and maintaining integration with the wider European energy system [47]. Since the Belgian government has committed to phasing out most nuclear electricity generation by 2025, there has been increasing uncertainty regarding the security of electricity supply. To address this, a capacity remuneration mechanism (CRM[1]) has been introduced in 2021 with the goal of ensuring electricity supply security during the reduction of nuclear generation [31, 47]. The transition measure to temporarily compensate for the loss of nuclear energy with new gas-fired power plants has sparked significant debate [6], largely due to the unprecedentedly high gas prices observed in 2022 [4], the goals to reduce fossil fuel dependency [47] and therefore the refusal to grant permits for gas-fired power plants [5].

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[1] Capacity Remuneration Mechanism: The introduction of a capacity remuneration mechanism for the Belgian market is part of the federal government's energy strategy, which lays out a number of new measures designed to guarantee Belgium's security of supply in the long term.

To mitigate the increasing risk of power outages, the government decided to extend the operating life of the two youngest (Doel 4 and Tihange 3) nuclear power plants by 10 years [41]. Upon the extension of Doel 4 and Tihange 3, Belgium will have a total capacity of 2077 MW for the next decade, from 2025 onwards. Consequently, a solution needs to be sought for the lost nuclear baseload capacity of 3866 MW. It is therefore imperative to contemplate the composition of Belgium's future energy landscape to minimize the risk of power outages.

The generation capacity in Europe is growing substantially. The adoption of clean energy is expected to cause a significant transformation in the global electricity systems. The decreasing costs of solar and wind power will enhance their utilization as electricity resources. However, the effects of renewable energy sources (RES) on market power remain inconclusive. The presence of high quantities of intermittent RES can pose significant challenges in ensuring a dependable and secure electricity supply. Recently, there has been increased focus on the "integration costs" linked to variable renewable generation [50]. Thermal generation is slightly decreasing overall — even though generation capacity of many technologies increases, there is considerable decommissioning of hard coal [38, 46]. So today's energy systems encounter novel challenges due to the integration of renewable energy sources. Rather than relying on a limited number of sizable power plants, a multitude of smaller units are dispersed throughout the country [57]. In order to evaluate various scenarios discussed later in this paper, the urbs software[2], developed at the Technical University of Munich [24], will be used. Similar problems have been modeled using the urbs software in previous studies [48, 57]. Urbs is a linear modeling framework that uses optimal dispatch models with an hourly resolution. The model produces an average capacity output generated in the course of one hour and can thus be seen as an energy output.

As baseload capacity diminishes and renewable energy gains dominance in the energy mix, energy security becomes more and more uncertain, increasing the risk of potential blackouts. This paper aims to assess the resilience of Belgium's future energy mix in meeting supply and demand by analyzing five distinct scenarios, each having a different set of generation capacity. Various parameters, such as interconnectivity and storage, will be adjusted to evaluate their impact on the overall system. These scenarios will be optimized with a focus on minimizing the total system cost. This leads to the two central research questions of this paper: How can Belgium's energy policy adapt to ensure the security of electricity supply in light of the phase-out of nuclear electricity generation by 2025, and what are the most cost-effective strategies for minimizing the risk of power outages?

The next section will provide more background information and a more in-depth look at several factors and current events contributing to this energy supply uncertainty, allowing us to better understand the challenges Belgium is

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[2] https://github.com/tum-ens/urbs

facing. In the third section, the methodology used will be discussed, along with a description of the various scenarios that were considered. The fourth section will present the main results of the study, followed by a discussion. Finally, the concluding section will summarize the key findings and offer recommendations for future research.

The determinants of supply uncertainty in Belgium

The cold spells in Europe are putting electricity supply under pressure. In various countries, grid operators are still able to meet the demand, but prices are soaring [8]. This trend is also observed in Belgium, where the supply of electricity is becoming more and more uncertain. The uncertainty is fueled by various factors including the planned closure of nuclear power plants, the refusal of permits for new gas-fired power plants, speculation on the gas market, increasing capacity in renewable energy sources, reduced import capabilities, and a growing trend towards electrification. Consequently, there is a need to carefully consider the future energy landscape.

Nuclear phase out saga

Nuclear power plants have a high ratio of capital costs to variable costs which has historically made them a reliable option for baseload power supply under past energy market conditions [54]. The discussion about the nuclear phase-out has been ongoing in Belgium for years. As of 2022, Belgium had 7 operational nuclear power plants located in two areas - Doel and Tihange. However, the recent closures of Doel 3 and Tihange 2 led to a reduction in the total capacity of nuclear sources from 5943 MW to 3929 MW [32]. The confirmation by Elia, the Belgian Transmission System Operator (TSO), of its concerns about potential energy supply problems from the winter of 2025 onwards [17, 30] has given rise to a new episode in the nuclear saga. The closure date of 2025 for the five remaining nuclear power plants in Belgium has been called into question. Various options have been considered, yet every one of them seems to raise specific concerns [20, 21]. Elia has expressed concerns about the strategy to extend Doel 4 and Tihange 3, but the Federal Agency of Nuclear Controle (FANC) has granted approval for their availability during the crucial winters of 2025-2027, addressing supply issues [20, 40, 41, 60].

With the extension of Doel 4 and Tihange 3 confirmed, Belgium will have a total capacity of 2077 MW for the ten-year period following 2025. Therefore, a solution must be found for the remaining 3866 MW. The lost capacity will be factored into *“Scenario 1: Planned Actions”* to assess the risk of potential blackouts. *“Scenarios 3: Small Modular Reactors”* and *“Scenario 4: Gas Transition”* will explore the feasibility of additional investments in respectively SMRs and gas-fired power plants to determine if new baseload capacity should be introduced.

Gas-fired power plants

With Belgium’s current capacity of gas-fired power plants, it is nearly impossible to compensate for the loss of nuclear energy. The total available capacity of contracted (CIPU) and non-contracted (non-CIPU) gas-fired power plants is 7285 MW, of which an average of 1926 MW was used, with peak performances reaching 5200 MW in 2022 [28]. It should also be noted that this available capacity includes peak power plants that are not designed for continuous operation and are inefficient, polluting, and expensive [**?**]. Moreover, many of the smaller

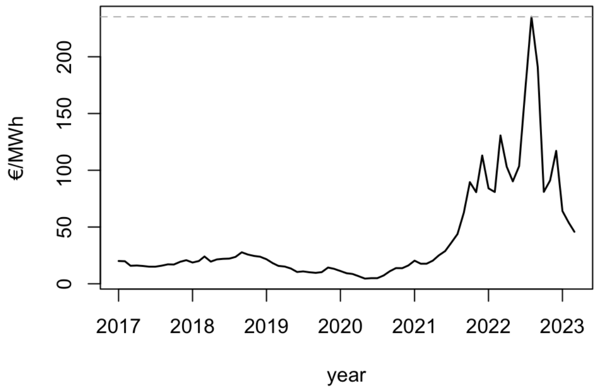

Figure 1: Gas prices soared in 2022 [26].

gas power plants are old, require frequent maintenance, and are more prone to failure due to intermittent operation, particularly during periods of low solar or wind energy availability.

Considering the Russian-Ukrainian conflict, the dependence on a single type of energy source also poses inherent risks when fuel prices on the spotmarket rise as shown in **Fig. 1**. The high gas prices made it unattractive to deploy gas-fired power plants. Nonetheless, these power plants are necessary to compensate for the loss of nuclear energy and to offset the intermittency of renewable energy sources. Therefore, the government has already awarded subsidies to two yet-to-be-built gas-fired power plants, one in Seraing and one in Les Awirs, near Liège [59]. *Scenario 1* will examine the planned measures to determine if they are adequate for ensuring energy supply, while *Scenario 4* will assess the additional capacity required and associated costs.

Increasing renewable energy sources

Belgium, like many other countries, is increasingly turning towards renewable energy sources to meet its growing energy needs. The rapid expansion in capacity has brought with it increased problems due to the variable and uncontrollable nature of wind and solar output. Both have profound effects on electricity markets: pushing down energy prices, due to the *merit order effect* and changing investment patterns [34, 53], increasing the need for infrastructure upgrades, and forcing countries to increase cooperation between their electricity markets to maintain efficiency and security [47, 55]. However, in the long term, the merit order effect can yield other outcomes. The continual decrease in wholesale prices diminishes the incentive for investments in fossil-fuel generators, crucial for providing stability and adaptability to the system, potentially jeopardizing security of supply [51]. From the perspective of conventional generators, the merit order effect exacerbates the challenge of insufficient revenue, a phenomenon referred to as the problem of "missing money" [50]. Moreover, the growing presence of renewable energy sources may weaken the efficacy of forward contracting in mitigating market power in wholesale electricity markets [3], potentially leading to elevated prices in situations where the capacity factor of renewable energy sources is low [52]. Between 2010 and 2020, renewable electricity production witnessed a more than fourfold increase, rising from 5.4 TWh to 23.4 TWh, especially driven by increased wind generation [47]. Belgium aims to collaborate with other European countries in developing the North Sea into a vast energy hub that generates its own clean and cost-effective electricity. In 2022 wind generation accounted for 8% of the total electricity consumption of households and businesses in Belgium [2, 32].

Weather conditions constitute a critical factor, as a surge in demand due to a severe cold spell, combined with a shortfall of wind turbines, can cause significant stress on the grid. Solar and wind power generation pose intermittent challenges for system operators, including variations in output by time of day, season, and even idiosyncratic factors. Their volatile character create shortfalls that must be dealt with. Despite the addition of significant capacity in the coming years [10, 13], renewable energy production in Belgium will never be sufficient to fully decarbonize the Belgian energy consumption [27, 35]. In *"Scenario 2: Net Zero Emissions"* an energy mix is studied that exclusively depends on renewable capacity. Parameters like interconnectivity and storage will be tweaked to determine its feasibility. The principal means of meeting power generation shortfalls today is spinning reserve, usually gas turbines intentionally running at less than full capacity, although it's anticipated that in the future, energy storage could replace spinning reserves. These may be ramped up or down very quickly to respond to very short term situations [**?** 56]. The principle of spinning reserves will be replicated in an iteration of both *Scenario 3* and *Scenario 4*.

Interconnected EU: Dependency of neighboring countries

The limited nuclear production in some countries, combined with the potential disruption of fossil fuel supply to power plants, poses a risk of high stress on the system. Because of Belgium's central location in Europe, the country plays an important role in the European energy system. Any incident abroad may have significant implications for the adequacy of the country's resources [36, 47]. The ongoing maintenance work has caused the shutdown of 19 out of 56 nuclear reactors in France, a country where more than 70 percent of its electricity demand is met through nuclear power [45, 49]. This presents major challenges for Europe [11, 39].

In **Fig. 2**, the monthly net export and import for Belgium to its neighboring are displayed over the past recent years. Overall, Belgium has transitioned in recent years from being a net importer of electricity to a net exporter. One of the main reasons for the increased exchange of electricity with neighboring countries is the installation of additional interconnection cables, enabling greater mutual exchange of electricity. As more fluctuating renewable energy sources are added

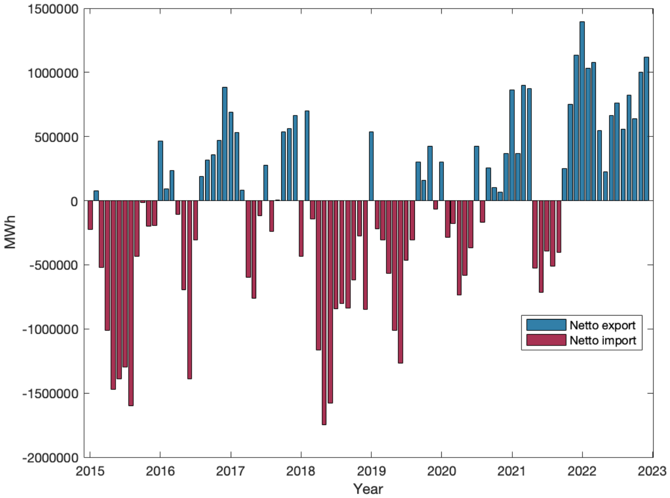

Figure 2: Netto Export-Import for Belgium to France (in MWh).

to the grid, the need to transport surpluses to areas in Europe where demand is highest also grows. The direction and volume of electricity transported depend on price differentials. If electricity is cheaper in Belgium than in a neighboring country, typically electricity will flow to the neighboring country, where it can be sold at a higher price, and vice versa [7, 47].

The need for flexibility

The need for flexibility is expected to significantly increase in the future. Batteries have the potential to assist in balancing the grid and mitigating imbalances within the system. Elia predicts that the demand for flexible injection capacity on the Belgian grid will rise from 3.3 GW presently to 5.3 GW by 2030. The primary function of the batteries is managing short-term shortages, rather than storing electricity for long periods or during the winter season. Roughly half of the flexible capacity should be capable of ramping up or down within fifteen minutes, for instance, in response to sudden changes in wind speeds [9, 28]. In *Scenario 2* will test if storage capacity can be used in a flexibile way to maintain balance of the grid.

Electricity Demand

Electricity demand is expected to grow in the next decade due to several factors such as population growth, economic development, and the increasing electrification such as the adoption of electric vehicles and renewable energy technologies. Furthermore, the industry also plays a significant role. The transition from oil and natural gas to electricity will result in a rapid increase in the electricity consumption of the Belgian industry [28].

Investment outlook

Electricity is the most efficient way to reduce CO_2 emissions in many processes, such as the transition to heat pumps, electric vehicles, ... The increasing investments in renewable energy, highlight the significance of cross border interconnections between countries to balance supply and demand. While RES have zero marginal cost, they still face challenges in terms of intermittency and the need for backup power sources [50]. With Elia's new Federal Development Plan [18, 35], it intends to ensure that the Belgian grid can accommodate the increase in renewable energy over the next decade. It seems inevitable that the network tariffs paid by households and businesses will also double as a result of the integration cost of RES [19, Newbery et al. [50]]. However, it addresses the challenges of decarbonization and ensures a sustainable, affordable, and reliable energy system for the future.

The next section will present further details regarding the methodology employed in this study. It explains the procedure and configuration of various scenarios. The challenges and background information provided in the past section will serve as inputs and constraints for establishing distinct scenarios.

Methodology

Modeling framework

The present study's methodology relies on the approach outlined in previous works [48, 57]. Specifically, the analysis employs the urbs software, which is a linear programming model specifically tailored to handle complex energy systems involving multiple commodities and sites. Notably, the model integrates investment decisions related to the addition or removal of energy generation, transmission, and storage capacity, in addition to optimizing dispatch decisions. It optimizes the dispatch model based on an hourly resolution. Ref. [48] has previously demonstrated the utility of this approach in achieving optimal outcomes in energy system management for the post-nuclear phase-out Belgian energy mix. Furthermore, the software is open-source and publicly available[3].

Prior to selecting various scenarios, the urbs software was subjected to testing. Initially, a model was employed to compare the output generated by the urbs dispatch model with the actual energy generation mix of Belgium in 2022. Subsequently, a model was developed to assess the occurrence of blackouts between 2022 and 2035, while maintaining historical production levels, without introducing new capacity, and adhering to the planned decommissioning and extension of nuclear power plants, and new CRM capacity as determined in the adequacy study by Elia[4]. In the investigated period (2022-2035), the demand exhibited a trend of growth as was previously outlined. By eliminating the possibility of import and export, blackouts could reveal our dependence on neighboring countries. A third model was evaluated by incorporating an import capacity source, which simulated the importance of an interconnected EU to eliminate blackouts.

Ultimately, a detailed interconnected network was established between Belgium and its neighboring countries (France, Germany, The Netherlands and United Kingdom) to enable energy exchange. This differs from the analysis outlined in Ref. [48] and gives a more realistic view on cross border capacity exchange. This final model serves as the base model for defining the different horizons for Belgian's future energy landscape, which will be outlined in the section on scenarios.

The goal of the study is to minimize system costs for the Belgian power system while fulfilling a given demand and CO_2 targets. This minimization is conducted with a classic deterministic perfect foresight approach, meaning all inputs are known. The uncertain parameters in this study are future demand profiles as well as the volatile wind, solar and water production of the system. In the event of an expansion scenario, the installed capacities of power plants, storage units, and transmission systems can be relaxed [57].

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[3] https://github.com/tum-ens/urbs

[4] Detailed information can be publicly consulted via https://www.elia.be/nl/publieke-consultaties/20221028_public-consultation-adequacy-study-2022-2032

Data preprocessing

To model the energy mix of 2022, this study relied on publicly available data regarding technological and economic parameters of installed capacities. For CIPU[5] contracted power plants, data was obtained from Elia's report on the adequacy and flexibility of the Belgian electric power system for the period of 2024-2034 [29]. For non-CIPU contracted power plants, the median from the existing technologies was taken. The installed capacities of neighboring countries was consulted via the ENTSO-E database [39]. If data points were missing, they were either replaced with the most recent available forecast or the previous data point of the actual timestep was used to model the next time step. Data on nuclear outages in France was consulted via the World Nuclear Association [62] and the reports by the EDF Group [25]. The data for wind, solar, and water were obtained from Elia's open database[6] [32], and the capacity factors were calculated for the five most recent years available (2018-2022)[7]. Capacity factors for neighboring countries were determined using data extracted from the ENTSO-E database [39]. In order to model demand for the energy mix of 2022, the total system load was employed. Data for Belgium was sourced from Elia's open database [32], while data for neighboring countries was extracted from the ENTSO-E database [39]. To project demand for future scenarios, consumption profiles were generated for each country. Belgium's consumption profile was derived from the RLP-profile[8], while neighboring countries' profiles were simulated based on historical load data. This resulted in a time series vector for each country, which was then multiplied by the estimated demand of each country for each time frame. For modeling the evolution of the energy mix from 2022 to 2035, the study incorporated the assumptions provided by the adequacy study by Elia for decommissioning, extension, and new CRM capacity [29]. Data on CO_2 emissions for different technologies were obtained from a study on CO_2 intensities [43], and the list of considered technologies is sourced from the adequacy study by Elia and the EIA [58].

Scenarios

Five different scenarios were developed, each with a distinct approach. Multiple iterations, as displayed in Appendix A, were performed on each scenario to observe the effects of changing variables on the energy mix. These scenarios were evaluated over a time horizon from 2025 to 2035, except for scenario 1, which

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[5] Contract for the Injection of Production Units

[6] During the examination of these time series conducted from Elia's open database, negative capacity was identified in the scaled and measured generation. These negative values were corrected by setting them to zero.

[7] The decision was made to utilize the load capacity factors of 2022 for all modeled scenarios, though it was feasible to opt for a random selection from these five vectors, leading to diverse results for the renewable energy generation.

[8] Real Load Profile. This is a type of consumption profile where the actual determined profiles of a specific group of consumers are applied to all individual consumers at the end of each month and can be consulted via https://www.synergrid.be/nl/documentencentrum/statistieken-gegevens/profielen-slp-spp-rlp

was also examined for the year 2022. The energy mix of neighboring countries, France, Germany, the Netherlands, and the UK, are also incorporated in the scenarios to better understand the implication of cross border trade. This will be especially crucial when the energy mix becomes more volatile in the scenarios, as evidenced by the results.

A brief explanation of each scenario is presented, followed by an analysis of the outcomes and a discussion. The initial stage *Setting the scene* entails comparing the energy production of the optimal model with that of the actual production in 2022 to provide context for the simulations. Each scenario is examined separately across its iterations and only the most significant outputs will be included in the results.

Scenario 1: Planned Actions (PA)

In this scenario, the planned (political) actions that are currently known are executed, taking into account the assumptions made in the Adequacy and Flexibility study by Elia. Four iterations are executed in this scenario, with each iteration relaxing a parameter, ultimately resulting in iteration 1C. First, only the demand in Belgium changes together with the production park (Folder1). Then, the demand in the neighboring countries evolves (Folder1A), followed by the production park of the neighboring countries (Folder1B). A final iteration will adjust the fuel and CO_2 prices over the measured time horizon (Folder1C). Folder 1B and 1C are closest to reality, differing only in fuel prices across the measured time horizon. This allows us to evaluate how fluctuations in fuel prices affect the composition of the energy mix. This scenario also includes a comparison between the actual production of the year 2022, obtained from the Elia open data platform, and the corresponding calculations generated by the model. Such comparison helps to put the model's performance into context with the actual measured results of 2022 and will be presented first in *Setting the scene.*

Scenario 2: Net Zero Emmisions (NZE)

In this scenario, only renewable energy sources are included in the energy mix. Four iterations are again carried out in this scenario. The focus of this scenario is to investigate the necessary (battery) storage capacity to attain an energy mix relying solely on renewable sources. Another key aspect of interest is the importance of imports and exports, given that there may not be sufficient power available everywhere at the same time. The first iteration aims to determine the ideal volatile energy mix when starting from no installed capacity. The second iteration takes into account the planned investment in renewable energy sources carried out in *Scenario 1* to assess whether it is sufficient and to determine the necessary storage capacity. The third and fourth iterations repeat the first two but focus on import and export, allowing for a maximum limit of 20,000 MW for cross border capacity exchange between each country.

Scenario 3: Small Modular Reactor (SMR)

This scenario introduces additional baseload from small modular reactors (SMRs) alongside renewable energy sources. Belgium aims to expedite the development of SMRs [14]. Small modular reactors are a type of nuclear reactor with smaller size and capacity in comparison to conventional large-scale nuclear reactors. Typically, SMRs may have a capacity of less than 300 MW, whereas large-scale nuclear reactors can have a capacity of up to 1,000 MW or more. The smaller size of SMRs offers advantages such as easier construction and maintenance, and they can be utilized for various applications, including as a source of baseload power for electricity grids [44, 61]. The objective of this scenario is to determine the required level of backup capacity to maintain a volatile energy mix and reduce dependence on batteries. The first iteration considers a scenario where planned investments in renewable energy (supplemented with battery capacity) are combined with investment in SMRs across all countries. The second iteration adheres to the planned actions of the surrounding countries carried out in *Scenario 1.* In Belgium, the total nuclear phase-out is halted (Doel 4 and Tihange 3), and the subsidies awarded in CRM 2025 for gas-fired power plants are put on hold. Instead, investments in SMRs are permitted to replace the lost capacity. The results will reveal significant implications for Belgian's export position.

Scenario 4: Gas Transition

This scenario is similar to *Scenario 3*, except that new combined cycled gas turbines (CCGT) are introduced instead of SMRs, following the principles of gas transition measures [6]. The same iterations are carried out as in *Scenario 3.*

Scenario 5: Free Willy

In this scenario, all new technologies are allowed, and two iterations are performed. In the first iteration, only new capacity is allowed in Belgium, while the planned actions in the surrounding countries are maintained. Then, the other countries will also be able to install new technologies. Initially, no CO_2 constraints are applied, but an increase of the CO_2 emission price is incorporated setting indirectly a constraint on the budget. The energy sector of the European Union (EU) is mandated to decrease CO_2 emissions by 40% by 2030, relative to 1990 levels, equating to a target of 756 million tonnes (Mton) of CO_2 emissions for the energy sector in 2030 [37].

Results

Setting the scene

To provide context for the simulation run in the urbs software, a comparison is made between statistical data from 2022 and the optimal dispatch model. As shown in **Tab. 1**, there are significant differences in the energy mix. The optimal model demonstrates a significant reduction in energy production from gas-fired power plants, contrasting the statistical data. Gas-fired power plants serve as the primary method for addressing power generation shortfalls [56]. One possible explanation for the decline is the increase in gas prices in 2022, as previously mentioned in the section on background information. The optimal model efficiently allocates the most affordable energy at the appropriate times throughout the entire time series. The energy generation previously produced from gas-fired power plants has been substituted by the energy produced by bioenergy-fueled power plants. While differences in the contribution of liquid fuel (turbojets) and water are also observed, their impact is negligible due to their minimal contribution to the overall energy mix. Nuclear power was almost the same, with only minor differences noticed because the optimal model did not consider any outages. The differences between the actual and optimal models are smaller when considering volatile energy sources. This is due to the fact that the optimal model employs the same load capacity factors and needs to make instantaneous decisions for these energy sources. The optimal model generated more solar energy than observed in the actual data because the installed capacity in the optimal model was taken at the end of the year, while less capacity was available at the start of 2022 in reality. The lower total demand[9] in the statistical model is due to a lack of data on the production of non-CIPU energy sources that are directly connected to the DSO network, which the optimal model considers. The total energy produced varies due to differences in cross border trade.

The presented findings reveal significant differences between import and export, as shown in **Tab. 2**. The optimal model utilized in this study does not take into account long-term cross border capacity, and solely focuses on five interconnected countries: Belgium, France, Germany, the Netherlands, and the UK. This approach leads to trade patterns that diverge from the interconnected system of the entire European Union. It is crucial to consider the simplified model in the context of the broader European interdependence. In 2021, France was a substantial exporter to Italy and Spain, two countries that are not accounted for in the model. Therefore, any inferences drawn from the model regarding the significance of cross border trade should be interpreted cautiously as they may not reflect the reality in its entirety due to the exclusion of certain countries. In the broader EU network, each country remains responsible for ensuring the balance of its own network. However, the optimal model efficiently allocates (volatile) energy, and such excess energy is instantly transferred. So it does allow us to perform an analysis on the impact of direct cross border trade.

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[9] The demand is computed as the sum of the energy generated by various energy sources, subtracting feedin and the energy exported and adding the energy imported. This leads to slightly different numbers than the demand shown in the demand tables in Appendix B.

Table 1: Comparison between statistical data and optimal data (in TWh) for each time horizon and errors.

Year	Nuclear	NaturalGas	Bioenergy	LiquidFuel	Water	WindOff	WindOn	Solar	Import	Export	Feedin	Blackout	Total Demand	Total Production
Energy mix														
2022 statistic	41.7057	16.8696	5.2125	0.0092	1.3861	6.6436	4.3656	6.4198	18.8857	-25.024	0	0	76.4738	82.6121
2022 optimal	43.0954	6.1543	9.351	1.0232	0.1516	6.6623	4.8406	7.982	14.6271	-11.9482	0	0	81.9392	79.2603
Energy mix % of production														
2022 statistic	50.48%	20.42%	6.31%	0.01%	1.68%	8.04%	5.28%	7.77%				0.00%		
2022 optimal	54.37%	7.76%	11.80%	1.29%	0.19%	8.41%	6.11%	10.07%				0.00%		
Import % of demand														
2022 statistic									24.70%					
2022 optimal									17.85%					
Surplus % of production														
2022 statistic										-30.29%	0.00%			
2022 optimal										-15.07%	0.00%			
errors														
E	1.3897	-10.7153	4.1385	1.014	-1.2345	0.0187	0.475	1.5622	-4.2586	13.0758	0	0	5.4654	-3.3518
MAD	2e-04	0.0012	5e-04	1e-04	1e-04	0	1e-04	2e-04	5e-04	0.0015	0	0	6e-04	4e-04
MSE	2e-04	0.0131	0.002	1e-04	2e-04	0	0	3e-04	0.0021	0.0195	0	0	0.0034	0.0013

Table 2: Comparison between statistical data and optimal data (in TWh) for each time horizon and errors

	Import					Export				
Years	Germany (i)	France (i)	The Netherlands (i)	UK (i)	Total import	Germany (e)	France (e)	The Netherlands (e)	UK (e)	Total export
Cross border trade										
2022 statistic	4.3820	2.2008	7.9741	4.3289	18.8857	-3.0732	-14.1609	-2.6125	-5.1774	-25.0240
2022 optimal	5.5339	8.8415	0.1122	0.1394	14.6271	-1.0471	-0.3455	-3.0375	-7.5181	-11.9482
errors										
E	1.1520	6.6408	-7.8618	-4.1895	-4.2586	2.0261	13.8153	-0.4250	-2.3407	13.0757
MAD	0.0001	0.0008	0.0009	0.0005	0.0005	0.0002	0.0016	0.0000	0.0003	0.0015
MSE	0.0002	0.0050	0.0071	0.0020	0.0021	0.0005	0.0218	0.0000	0.0006	0.0195

Planned Actions (Scenario 1)

Upon an increase in demand from neighboring countries, blackouts occur systematically from 2030. As presented in **Tab. 3** and **Tab. 4**, a total energy shortage of 0.0052 TWh is observed in both *Iteration 1B* and *1C* in 2030, which increases fivefold in 2035. In the simulation, a blackout is defined as a last resort when no other options are available. However, given the higher level of freedom in energy exchanges in the simulations, the probability of blackouts in reality is likely to be higher. The uncertainty increases due to the lower baseload capacity of nuclear energy available in Belgium, which is largely replaced by volatile energy sources. Import supports more than half of the demand from 2025 onwards, which is not necessarily unfavorable, considering that over half of the production is exported from 2025 onwards. One of the main contributing factors to this trend is the increasing reliance on volatile energy sources in Belgium's energy mix as well as in neighboring countries over the time horizon. The data indicates a substantial rise in the share of volatile energy sources in Belgium's energy mix. The contribution of these sources increases from 25% in 2022, going to 35% in 2025, and surpassing 60% from 2030 onwards.

Another notable observation regarding the cross border energy exchanges among different countries is that most of the Belgian energy is exported to Germany. This trend is a result of Germany's decision to shut down all of its nuclear power plants and shift towards renewable energy sources [15], thereby increasing its reliance on other countries when its demand is not adequately supported.

Upon analyzing the effects of adjusting prices over time, notable differences in the energy mix are observed between *Iteration 1B* and *1C*. In *Iteration 1C*, assumptions are made regarding a decrease and stabilization of the gas price and an increase in the CO_2 price per ton. The decrease in gas prices makes it more cost-effective to include gas in the energy mix, especially with the introduction of new gas power plants in the energy mix from 2025 (CRM 2025) that are more efficient and less polluting. Consequently, the use of turbojets and bioenergy-fueled plants decreases, while the use of gas increases. In *Iteration 1C*, the increase in CO_2 price leads to a notable reduction in CO_2 emissions compared to *Iteration 1B*. It indirectly imposes a constraint on the selected energy mix. As they face lower penalties and possess greater economic value, the system increasingly depends on energy sources that emit the least CO_2.

Table 3: Energy mix of Belgium (in TWh) for each time horizon (Folder1B).

Year	Nuclear	NaturalGas	Bioenergy	LiquidFuel	Water	WindOff	WindOn	Solar	Import	Export	Feedin	Blackout	Total Demand	Total Production
Energy mix														
2022	43.0954	6.1543	9.351	1.0232	0.1516	6.6623	4.8406	7.982	14.6271	-11.9482	0	0	81.9392	79.2603
2025	29.1981	6.305	6.7829	0.7624	0.1662	6.6623	6.2195	11.0436	54.4635	-31.4846	0	0	90.1187	67.1398
2030	14.0032	6.5311	5.1214	0.5818	0.1831	16.9799	8.5176	15.308	85.8654	-35.7323	-3.8339	0.0052	113.5304	67.2313
2035	12.9192	8.3369	4.7312	0.5627	0.1977	16.9799	10.3561	18.9163	108.7518	-39.7385	-10.0726	0.0257	131.9664	73.0257
Energy mix % of production														
2022	54.37%	7.76%	11.80%	1.29%	0.19%	8.41%	6.11%	10.07%				0.00%		
2025	43.49%	9.39%	10.10%	1.14%	0.25%	9.92%	9.26%	16.45%				0.00%		
2030	20.83%	9.71%	7.62%	0.87%	0.27%	25.26%	12.67%	22.77%				0.01%		
2035	17.69%	11.42%	6.48%	0.77%	0.27%	23.25%	14.18%	25.90%				0.04%		
Import % of demand														
2022									17.85%					
2025									60.44%					
2030									75.63%					
2035									82.41%					
Surplus % of production														
2022										-15.07%	0.00%			
2025										-46.89%	0.00%			
2030										-53.15%	-5.70%			
2035										-54.42%	-13.79%			
growth														
2022														
2025	-32.25%	2.45%	-27.46%	-25.49%	9.60%	0.00%	28.49%	38.36%	272.35%	163.51%			9.98%	-15.29%
2030	-52.04%	3.59%	-24.50%	-23.69%	10.22%	154.87%	36.95%	38.61%	57.66%	13.49%			25.98%	0.14%
2035	-7.74%	27.65%	-7.62%	-3.28%	7.95%	0.00%	21.58%	23.57%	26.65%	11.21%	162.72%	391.31%	16.24%	8.62%

Table 4: Energy mix of Belgium (in TWh) for each time horizon (Folder1C).

Year	Nuclear	NaturalGas	Bioenergy	LiquidFuel	Water	WindOff	WindOn	Solar	Import	Export	Feedin	Blackout	Total Demand	Total Production
Energy mix														
2022	43.0954	6.1543	9.351	1.0232	0.1516	6.6623	4.8406	7.982	14.6271	-11.9482	0	0	81.9392	79.2603
2025	29.1704	8.9172	6.754	0.0044	0.1662	6.6623	6.2195	11.0436	56.9366	-35.8112	-0.0015	0	90.0614	68.9375
2030	14.0032	6.5311	5.1214	0.5818	0.1831	16.9799	8.5176	15.308	85.8654	-35.7323	-3.8339	0.0052	113.5304	67.2313
2035	13.0598	16.2599	2.2331	0.0269	0.1977	16.9799	10.3561	18.9163	106.8768	-43.0063	-10.0249	0.0261	131.9014	78.0557
Energy mix % of production														
2022	54.37%	7.76%	11.80%	1.29%	0.19%	8.41%	6.11%	10.07%				0.00%		
2025	42.31%	12.93%	9.80%	0.01%	0.24%	9.66%	9.02%	16.02%				0.00%		
2030	20.83%	9.71%	7.62%	0.87%	0.27%	25.26%	12.67%	22.77%				0.01%		
2035	16.73%	20.83%	2.86%	0.03%	0.25%	21.75%	13.27%	24.23%				0.03%		
Import % of demand														
2022									17.85%					
2025									63.22%					
2030									75.63%					
2035									81.03%					
Surplus % of production														
2022										-15.07%	0.00%			
2025										-51.95%	0.00%			
2030										-53.15%	-5.70%			
2035										-55.10%	-12.84%			
growth														
2022														
2025	-32.31%	44.89%	-27.77%	-99.57%	9.60%	0.00%	28.49%	38.36%	289.25%	199.72%			9.91%	-13.02%
2030	-52.00%	-26.76%	-24.17%	13 061.73%	10.22%	154.87%	36.95%	38.61%	50.81%	-0.22%	256 989.00%		26.06%	-2.48%
2035	-6.74%	148.96%	-56.40%	-95.38%	7.95%	0.00%	21.58%	23.57%	24.47%	20.36%	161.48%	398.51%	16.18%	16.10%

Net Zero Emmission (Scenario 2)

A scenario consisting solely of renewable energy sources may seem unrealistic, but it is an interesting scenario to test for its theoretical feasibility. In this scenario, cross border capacity and storage capacity play a vital role. *Iterations 2* and *2B* are combined, as are *Iterations 2A* and *2C*. The pairs represent two identical scenarios[10] Future iterations could consider incorporating limitations based on available surface area, as outlined in Ref. [48]. However, within each pair, the second iteration (*2B,2C*) is given a higher cross border capacity for installation to study what the impact of interconnectivity will be.

Table 5: Pre-installed capicity against new installed capacity in Belgium (in GW) over the observed time horizon (Folder2).

	Water		Solar		WindOff		WindOn	
Year	Inst.	New	Inst.	New	Inst.	New	Inst.	New
2025	0.133	0	0	0	0.0000	23.6421	0	0
2030	0.133	0	0	0	23.6421	6.0673	0	0
2035	0.133	0	0	0	29.7094	5.7062	0	0

Table 6: Pre-installed capicity against new installed capacity in Belgium (in GW) over the observed time horizon (Folder2B).

	Solar		Water		WindOff		WindOn	
Year	Inst.	New	Inst.	New	Inst.	New	Inst.	New
2025	0.133	0	0	0	0.0000	10.6308	0	0
2030	0.133	0	0	0	10.6308	5.1072	0	0
2035	0.133	0	0	0	15.7380	7.9816	0	0

The first pair of iterations, 2 and 2B, start with zero installed capacity. The energy mix reveals a distinct pattern where the majority of countries opt for offshore wind capacity in conjunction with battery storage, except for France, where solar energy is also included. Offshore wind is the most efficient and consistent volatile energy source. The growth of offshore wind is projected to increase significantly in the coming years, as the deployment of turbines at sea exploits the enhanced wind conditions [1]. However, *Iteration 2B* requires much less offshore capacity than *Iteration 2*. The total installed offshore capacity in 2035 is 15.7 GW in iteration 2B compared to 29.7 GW in *Iteration 2*, as shown in **Tab. 5** and **Tab. 6**.

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[10] In this scenario, there is an absence of a constraint on the maximum feasible installed offshore wind capacity, which does not reflect reality.

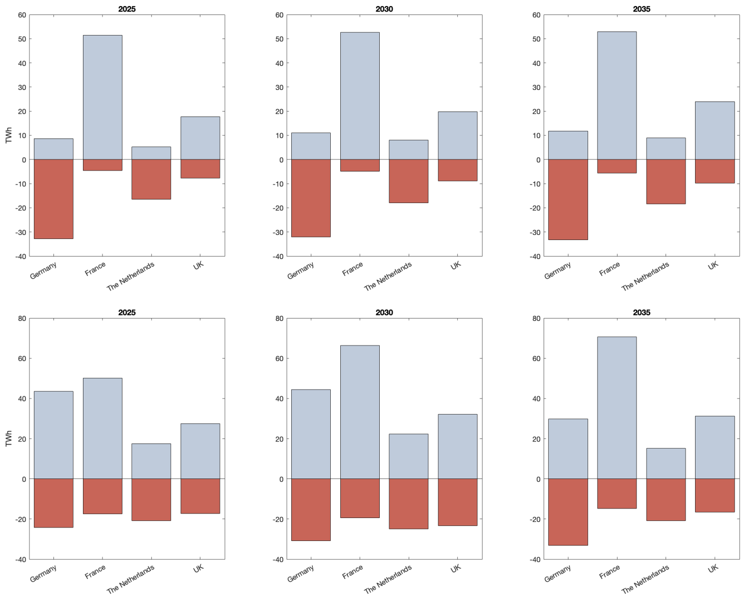

Figure 3: Cross border energy trade (in TWh) over the observed time horizon (top: Folder2; bottom:Folder2B).

As expected, an increase in cross border trade is observed in *Iteration 2B*. However, the pattern of trade between the countries differs as shown in **Fig. 3**. In *Iteration 2B*, there is a more even distribution of energy import and export among countries. The most notable difference between *Iteration 2* and *Iteration 2B* lies in battery storage. While almost 3 TWh of battery capacity is required by 2035 in *Iteration 2*, only 0.09 TWh is needed in iteration 2B, as shown in **Tab. 7**.

During the analysis of *Iterations 2A* and *2C*, where all planned installed renewable capacity is considered, it becomes apparent that both scenarios require the installation of additional offshore capacity[11]. However, the total newly installed capacity is again lower in *Iterations 2C* compared to *Iterations 2A*, supporting the fact that an increase in cross border capacity leads to a more efficient utilization of volatile energy production. Upon examining the trade patterns, a much less erratic pattern of imports is observed compared to *Iterations 2 and 2B*, as shown in **Fig. 4**. Import and export are much more balanced, indicating a more diversified distribution of renewable energy sources across all countries.

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[11] In future calculations, it would be valuable to include iterations that restrict the possibility of additional installation of renewable capacity for Iterations 2A and 2C.

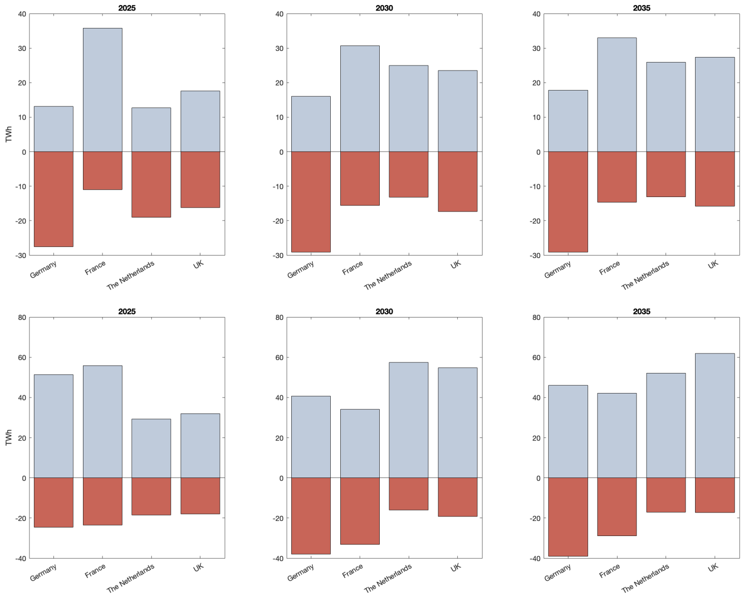

Figure 4: Cross border energy trade (in TWh) over the observed time horizon (top: Folder2A; bottom: Folder2C).

Table 7: Needed battery storage capacity to support renewables (Storage in TWh, Power in GW) for each time horizon.

	Folder2				Folder2B			
	Storage		Power		Storage		Power	
Year	Inst.	New	Inst.	New	Inst.	New	Inst.	New
2025	1.4190	1.4190	5.6850	5.6850	0.0000	0.0000	0.0000	0.0000
2030	2.1331	0.7141	9.7236	4.0385	0.0000	0.0000	0.0000	0.0000
2035	2.8058	0.6727	10.8884	1.1648	0.0861	0.0861	0.3303	0.3303

Small Modular Reactors & Gas Transition (Scenario 3 & 4)

In this section, there is a comparison not only among the iterations within a specific scenario but also between both scenarios to evaluate which is better suited to contribute to baseload and peak capacity in a renewable-dominated energy mix. The comparison starts with Small Modular Reactors (SMRs) and is subsequently extented to inlude gas-fired power plants.

In *Iteration 3*, there is an increase of 10 GW of new installed SMR capacity in Belgium in 2025, and an installed capacity of approximately 13.5 GW in 2030 and 2035. Despite the increase in the maximum value of the required capacity

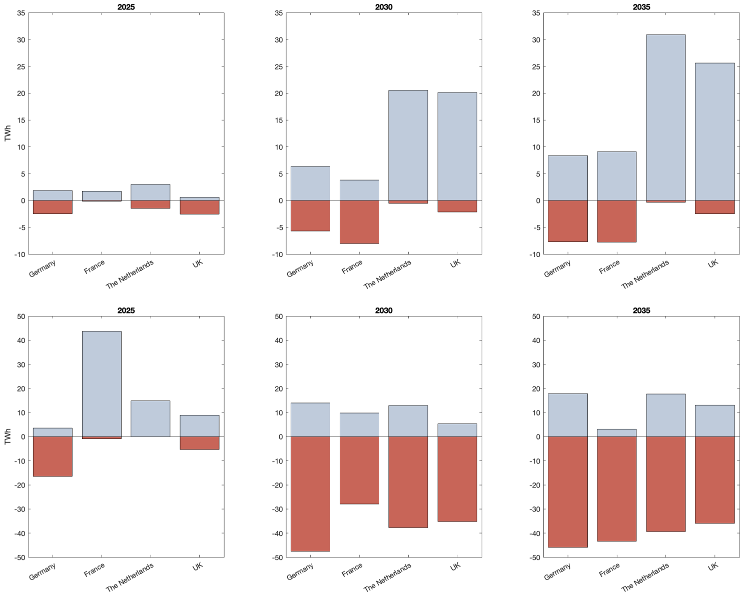

Figure 5: Cross border energy trade (in TWh) over the observed time horizon (top: Folder3; bottom: Folder3A).

in this scenario, the mean percentage capacity use[12] over the entire time horizon decreases. This suggests that, despite the addition of new SMR capacity to address peak demand, the efficiency of RES improves as a result of increased interconnectivity. This confirms previous findings from *Scenarios 1* and *2* that highlight the importance of interconnectivity. This is also supported when examining the cross border energy trade between Belgium and other countries in **Fig. 5**. As of 2030, a significant portion of Belgium's energy imports is attributed to both the Netherlands and the United Kingdom, countries primarily focused on the installation of volatile energy sources.

When *Iteration 3* is compared with *Iteration 3A*, an unexpected outcome occurs. While a decrease in baseload capacity in SMRs was expected in *Iteration 3A*, there is actually a significant increase in Belgium. Belgium currently provides baseload capacity for the entire system, facilitating a smoother transition to renewable energy sources in neighboring countries. This is noticeable in the mean percentage capacity usage; in *Iteration 3*, the usage dropped to 25% in 2035. In *Iteration 3A*, however, the installed capacity nearly triples, with an average utilization of 70% of the installed capacity[13]. This trend is also evident in **Fig. 5**, which showcases Belgium's robust export position in the energy sector. This signifies that Belgium has the opportunity to sell a larger amount

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[12] See Appendix B section 2.3.2.3, Table 79

[13] See Appendix B section 2.3.3.3, Table 88

of energy to neighboring countries, which can give Belgium more negotiating power, potentially yielding economic benefits. There is a significant reduction in the CO_2 emissions, when comparing *Iteration 3* to *Iteration 1C*.

Following that, *Scenario 4* will be analysed and together with *Scenario 3*, and *Iteration 3* and *3A* will be compared respectively with *Iteration 4* and *4A*. When examining the energy mix of *Iteration 4*, as depicted in **Tab. 8**, it becomes immediately apparent that blackouts occur. Despite the absence of a total capacity limit for installation of new gas-fired power plants within the system, generating a blackout seems to be a *"cheaper"* solution compared to installing additional capacity dedicated to this purpose. Furthermore, the blackout only occurs at a specific time step (570). A more comprehensive analysis of this time step reveals that there is no possibility for importing energy from other countries within the model at this particular moment. On average, there is a higher installed capacity of gas power plants compared to SMRs. This can be attributed to two factors. First, the reduced installation of batteries results in a decrease in storage capacity. Second, gas-fired power plants have significantly lower fixed and variable costs, as illustrated in **Tab. 9** . However, despite the lower fixed and variable costs, the operational cost for the total system is considerably higher for a scenario focused on gas-fired power plants. This is primarily due to the fact that a MW generated from gas-fired power plants is penalized more heavily as the CO_2 emission costs increase. This trend is also reflected in the total CO_2 emissions produced, confirming previous findings outlined in Ref. [48].

Table 8: Energy mix of Belgium (in TWh) for each time horizon (Folder4).

Year	New CCGT	Water	WindOff	WindOn	Solar	Import	Export	Feedin	Blackout	Total Demand	Total Production
Energy mix											
2025	55.5789	0.1613	6.6623	9.8515	11.0436	14.7467	-8.1129	-0.0101	0.0013	89.9225	83.2989
2030	48.9014	0.1613	16.9799	8.5176	15.4173	39.7699	-16.5453	-0.1077	0.0049	113.0994	89.9825
2035	47.2111	0.1613	16.9799	10.3561	18.9163	58.2094	-20.1502	-0.0763	0	131.6076	93.6247
Energy mix % of production											
2025	66.72%	0.19%	8.00%	11.83%	13.26%				0.00%		
2030	54.34%	0.18%	18.87%	9.47%	17.13%				0.01%		
2035	50.43%	0.17%	18.14%	11.06%	20.20%				0.00%		
Import % of demand											
2025						16.40%					
2030						35.16%					
2035						44.23%					
Surplus % of production											
2025							-9.74%	-0.01%			
2030							-18.39%	-0.12%			
2035							-21.52%	-0.08%			
growth											
2025											
2030	-12.01%	0.00%	154.87%	-13.54%	39.60%	169.69%	103.94%	963.69%	272.77%	25.77%	8.02%
2035	-3.46%	0.00%	0.00%	21.58%	22.70%	46.36%	21.79%	-29.17%	-100.00%	16.36%	4.05%

Table 9: Comparing costs between SMRs and New CCGT.

Powerplant	Investment costs [€/MW]	Anual fixed cost [€/MW/a]	Variable cost [€/MWh]
Small Nuclear Reactor	5695720	87400	2.8
New CCGT	950000	35000	2.0

When comparing *Iteration 3A* to *Iteration 4A*, there is a significant difference in the total energy production, as shown in **Fig. 6**. Cross border trade between the two iterations exhibits notable variations. In *Iteration 4A*, there is a substantial increase in energy imports from neighboring countries. Furthermore, Belgium's strong export position observed in *Iteration 3A* completely diminishes in *Iteration 4A*.

Table 10: Mean percentage capacity use.

	Folder3A	Folder4A
Year	SMR	NaturalGas
2022	0.00%	16.90%
2030	80.76%	3.31%
2035	70.54%	2.92%

Moreover, the utilization of the installed capacity in *Iteration 4A* demonstrates inefficiencies. A detailed analysis of the mean percentage capacity use exposes notable disparities between the two iterations. Within *Iteration 4A*, the utilization of capacity is significantly lower as shown in **Tab. 10**, indicating inconsistent operation at maximum capacity. This inefficiency in capacity utilization raises concerns regarding the optimal allocation of resources and the efficient generation of energy.

Free Willy (Scenario 5)

In *Iteration 5*, diesel engines are exclusively chosen, as shown in **Fig. 7**, mitigating minor energy shortages. Despite a significant installed capacity, the energy output is found to be low. This can be attributed to the combination of a very small mean percentage capacity use and a relatively high standard deviation, implying that the diesel engines have been utilized infrequently. A more detailed analysis of the time series reveals that in 2025, the diesel engines ware only active for 430 time steps (1 hour) to support the energy demand, which further decreased to a mere 30 time steps in 2030.

The primary reason for selecting diesel engines in this scenario is their lower investment cost. At the start of the time frame (2025), the role of CO_2 emission pricing in operational costs is less prominent. Consequently, in 2035, the decision is made to no longer rely on diesel engines, and instead, the energy demand of Belgium is entirely met through import and storage capacity, as shown in **Fig. 8**. Notably, the required storage capacity exhibits substantial variations in this iteration. While no storage capacity is demanded in 2025, there is a significant increase in 2030, followed by a subsequent decline in 2035. *Iteration 5* exhibits minimal differences in the setup compared to *Iteration 1C*, with the exception that *Iteration 5* allows for a free choice of the production park in Belgium and can add additional storage capacity to the whole system. The substantial reduction in operational costs in *Iteration 5*, as shown in **Tab. 11**, highlights

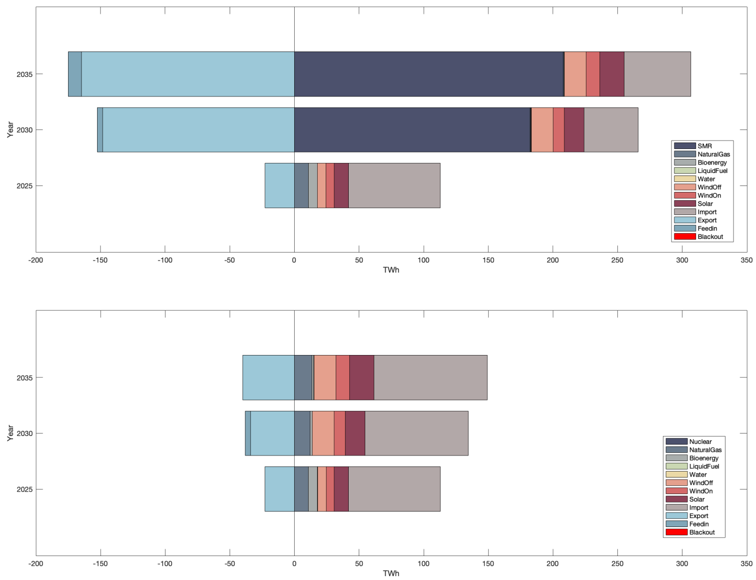

Figure 6: Energy mix (in TWh) over the observed time horizon (top: Folder3A; bottom: Folder 4A).

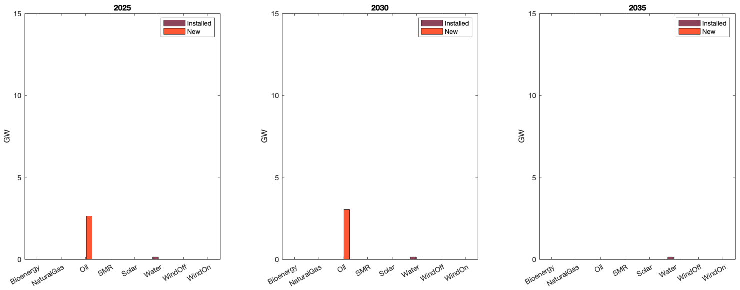

Figure 7: New installed capacity of Belgium (in GW) over the observed time horizon (Folder5).

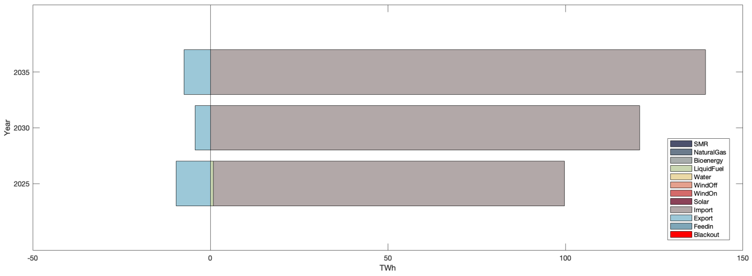

Figure 8: Energy mix (in TWh) over the observed time horizon (Folder5).

the efficiency gains achieved through improved utilization of volatile energy sources of neighboring countries via import and a more effective distribution of energy within the European system. This emphasizes the importance of strategic decision-making regarding storage capacity and production park selection to optimize the overall performance and cost-effectiveness of the energy system.

Table 11: Comparing total system costs for Folder1C and Folder5 for the observed timehorizon, in € Billion.

Year	Investment cost	Operational cost
Folder1C		
2025	13.40	61.26
2030	30.15	165.93
2035	21.78	572.40
Folder5		
2025	13.81	62.59
2030	35.31	60.52
2035	30.52	65.84

In *Iteration 5A*, the cross border capacity has been reduced from 8000 MW between countries to 2000 MW, which immediately impacts the installed capacity. Throughout the entire time horizon, a baseload capacity of SMRs is consistently chosen, as illustrated **Fig. 9**. The high mean percentage capacity use indicates that these SMRs serve as a reliable baseload source, providing a constant energy output throughout the year. Additionally, the energy demand is supported by a combination of gas-fired power plants and diesel engines, as shown in **Fig. 10**. However, diesel engines are rarely utilized due to their heavier penalty compared to energy generated by gas-fired power plants. Another notable aspect of this scenario is the diminished dependence on storage capacity, attributed to the heightened baseload capacity serving as a flexible component.

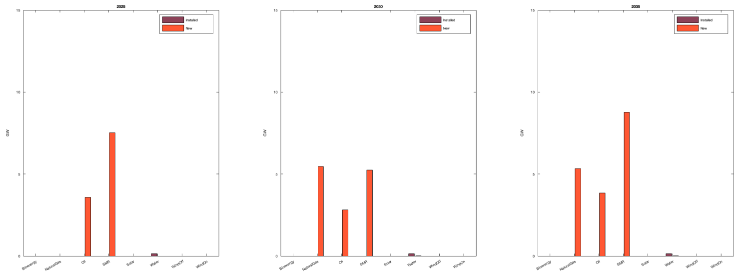

Figure 9: New installed capacity of Belgium (in GW) over the observed time horizon (Folder5A).

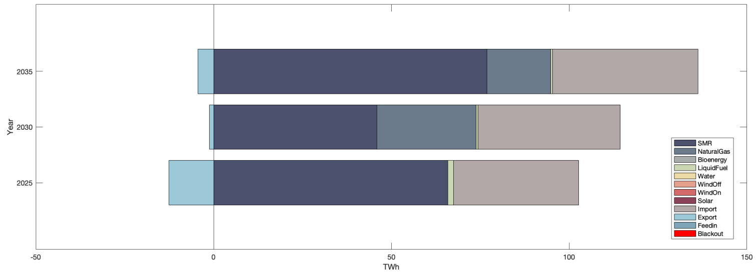

Figure 10: Energy mix (in TWh) over the observed time horizon (Folder5A).

Discussion

Planned Actions (Scenario 1)

The growing share of volatile energy sources in both Belgium's energy mix and those of its neighboring countries amplifies the uncertainty surrounding energy security. This underscores the growing significance of intraday trading in the energy sector, establishing cross-border capacity to guarantee the efficient distribution of energy resources. While this increased reliance on volatile energy is not necessarily negative, interconnectivity plays a crucial role in diversifying the risk of blackouts and potentially reducing energy costs for Belgian consumers. Nevertheless, if multiple countries experience the same variability and intermittency issues, it could result in a shortage of energy across the region, leading to a potential blackout. Interconnectivity is most valuable when it involves uncorrelated regions.

Renewable energy is the most cost-effective form of energy, it is likely to be prioritized when it is available in surplus in other countries. This has trade implications as it can lead to an increased demand for cross border trade of renewable energy, benefiting countries with a surplus of renewable energy and reducing the reliance on non-renewable energy sources. It supports the fact that import and export of energy between countries play a significant role in ensuring a reliable and sustainable supply of energy. Diversification of energy sources and cross border trade can mitigate the risks of supply disruption and potentially reduce the overall cost of energy for consumers. The growing use of volatile energy sources also has impact on storage capacity. In Belgium, the Coo pumped storage plant serves as a backup to maintain the stability of the power grid during peak demand or unexpected outages. The simulations demonstrate a substantial increase in the utilization of the Coo pumped storage capacity, primarily attributed to the surge in volatile energy sources and their intricate interplay. While this does not accurately reflect the usage in reality, it also underlines the importance of storage capacity as volatile energy sources become more important.

Net Zero Emmission (Scenario 2)

First, when cross border capacity is increased, a more even distribution of energy import and export among countries is noticed. This emphasizes the potential advantages of interconnectivity and direct trade in achieving energy security and stability, as countries can enhance their energy demand by mutually complementing each other and decreasing reliance on fossil-fueled power plants. Second, a higher cross border capacity, lowers the need for battery storage. Battery storage requires significant investment, so reducing the required storage capacity can lead to significant cost savings. This has important implications for the cost and feasibility of a scenario where the dominant share of energy production is renewable. By reducing the reliance on battery storage, such a scenario may be more feasible and sustainable in the long run.

Import and export are much more balanced in the second pair of iterations (*2A & 2C*) than the first pair (*2 & 2B*), indicating the importance of a diversified mix of renewable energy sources across all countries. This diversified mix contributes to increased variability in the energy mix, ultimately diminishing correlation between interconnected regions and mitigating the issue of intermittency. As a result, there is a more effective utilization of energy resources and a reduced dependency on battery storage to compensate for intermittent supply. Therefore, less battery storage is required for Belgium, as the country benefits from a more stable and diverse energy supply. It is noteworthy that while all other countries in the system install new battery capacity[14], Belgium requires a comparatively lower amount. The favorable geographic position of Belgium, being linked directly to four countries, may have contributed to its lower battery storage requirements compared to other countries in the analyzed scenarios.

It is clear that increased emphasis on cross border capacity and a diversified renewable energy mix results in lower investments in new energy and storage capacity. This suggests that intra-day trade can play a crucial role in realizing an energy system dominated by renewable sources. Understanding trade patterns and potential impacts on energy security is crucial to fully harness the advantages of direct cross-border trade.

Small Modular Reactors & Gas Transition (Scenario 3 & 4)

The results indicate that SMRs not only substitute for gas production but also decrease the output of bioenergy-fueled power plants and turbojets, thereby reducing overall CO_2 emissions. Energy produced from gas-fired sources is considerably more expensive than energy generated from SMRs, mainly due to the associated CO_2 price. The contrasting energy mixes and the shift in import-export dynamics underscore the impact of the CO_2 pricing mechanism on the cost competitiveness of gas-fired produced energy. The observed variations in *Scenario 3* and *Scenario 4* on capacity utilization emphasize the importance of evaluating not only the installed capacity but also its utilization rates, thereby facilitating the development of a more efficient and optimized energy system. In a scenario where Belgium invests in SMRs, it assumes a crucial central role in European energy dispatching, contributing to cost-effective flexibility for the optimal utilization of renewable energy sources.

Free Willy (Scenario 5)

The substantial reduction in operational costs in *Iteration 5*, emphasizes the importance of strategic decision-making regarding storage capacity and production park selection to optimize the overall performance and cost-effectiveness of the energy system. The decrease in cross border capacity has significant implications for the integration of renewable energy sources. With the reduced capacity, the surplus renewable energy cannot be efficiently traded or stored, leading to missed opportunities for utilizing inexpensive renewable energy. This again highlights the importance of adequate cross border capacity in facilitating the storage and utilization of renewable energy. An analysis of the CO_2 emissions

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[14] The figures have been calculated but are not included in Appendix B.

reveals a consistent trend: when the cross border capacity is lower, the total CO_2 emissions of the entire system tend to be higher. Furthermore, it is observed that both investment and operational costs increase as a result. This can be partially attributed to the reduced efficiency in utilizing the installed capacity of renewable energy sources.

The relationship between cross border capacity and CO_2 emissions can be explained by the interplay of various factors. When the cross border capacity is higher, it allows for the transmission of a greater amount of electricity from neighboring regions. This, in turn, enables the integration of more renewable energy into the system. However, if the system is unable to efficiently harness and utilize this increased renewable energy supply, it may result in under utilization or curtailment of these resources. This can lead to a higher reliance on conventional power sources, such as fossil fuel-based generation, to meet the energy demand. These conventional sources typically have higher CO_2 emissions associated with their operation. Consequently, the overall CO_2 emissions of the system increase when the installed capacity of renewable energy is not efficiently utilized due to limitations in cross border capacity.

Conclusions

The expansion of generation capacity in Europe is witnessing substantial growth, primarily driven by the adoption of clean energy sources that are poised to transform global electricity systems. However, the rapid growth in capacity presents challenges due to the variable and uncontrollable nature of renewable energy. This poses profound effects on electricity markets, necessitating infrastructure upgrades, and emphasizing the need for enhanced cooperation among countries to ensure efficiency and security.

Interconnectivity plays a crucial role in optimizing the utilization of RES and facilitating the decarbonization of the energy sector, particularly given Belgium's central location in Europe. In addressing the intermittency challenges inherent in RES, both interconnectivity and storage capacity emerge as vital factors. They are instrumental in managing fluctuations in energy production, providing a dependable energy supply, especially during periods of reduced baseload capacity. Therefore, careful consideration of Belgium's future energy landscape is essential to minimize the risk of power outages and ensure a reliable energy supply. Despite anticipated substantial capacity additions in the coming years, it is acknowledged that Belgium's renewable energy production alone may not suffice for complete decarbonization of its energy consumption, emphasizing the ongoing need for support from baseload capacity.

The analysis of planned actions (scenario 1) reveals the risks of blackouts, primarily due to the lower baseload capacity of nuclear energy and the growing share of renewable energy sources in Belgium and neighboring countries. To mitigate these risks, solutions must be identified. The results of scenario 2 demonstrate that replacing baseload capacity with renewable capacity requires an increased emphasis on cross border capacity and a diversified renewable energy mix to address intermittency issues, resulting in reduced investment of new energy sources. Cross border trade plays a crucial role in mitigating intermittency issues, reducing the reliance on extensive battery storage.

Furthermore, a system reliant on renewable energy sources supported by baseload capacity from small modular reactors offers numerous advantages, including higher output resulting in a stronger export position, lower CO_2 emissions, and reduced operational costs compared to additional baseload capacity from gas-fired power plants.

A decrease in cross border capacity has significant implications for the integration of renewable energy sources. With the reduced cross border capacity, the surplus renewable energy cannot be efficiently traded or stored, leading to missed opportunities for utilizing renewable energy. The inverse correlation observed between cross border capacity and factors such as storage capacity, CO_2 emissions, and costs in the analyzed scenarios demonstrates the importance of efficiently utilizing the installed capacity of renewable energy sources. Adequate cross border capacity, a diversified renewable energy mix and storage capacity are crucial for maximizing the integration of renewable energy and minimizing reliance on conventional, higher-emitting power sources, thus reducing both environmental impacts and economic costs.

In conclusion, the examination of various scenarios in this study demonstrates the diverse potential trajectories for Belgium's energy landscape. Regardless of the specific scenario, one consistent finding is the crucial role played by interconnectivity with the wider European system. Interconnectivity provides flexibility and is instrumental in achieving decarbonization objectives and establishing a resilient and sustainable energy future.

Future research

A potential future research topic that focuses on geographical grid granularity could involve studying the implications of adopting a more detailed spatial resolution in energy grid modeling and planning, more known as *"nodal pricing"*. It would contribute to a more nuanced understanding of the interplay between spatial variations in energy generation. Also further research can incorporate not only CO_2 emissions but also other pollutants such as NOx, NH_3, and SO_2 emissions from energy production. By considering the environmental impact of various energy sources and technologies comprehensively, the study would aim to understand and address the broader implications of energy systems on air quality and public health.

Energy system modelers require high resolution time series of power output from renewable energy, as their variable and unpredictable nature poses increasing challenges for the electricity system [55]. It must be noted that an average capacity over one hour will smooth out certain peaks and shortfalls. A smaller time granularity should be more effective in capturing the volatility of renewable sources such as wind and solar.

The optimal model is a valuable tool for optimizing the allocation of energy resources, but it fails to fully account for the complexities of real-world grid operations. Specifically, the model's optimization process may not accurately reflect the realities of forward cross border capacity trades, potentially resulting in inaccurate predictions of energy production. Consequently, adjustments may be necessary to align the model's projections with actual outcomes. Nevertheless, the model is well-suited to assess volatile energy sources and can efficiently allocate excess energy. Moreover, the model can assist in identifying potential areas for improvement in the energy mix. It can also assess the consequences of scaling up renewable energy sources, analyze the influence of interconnectivity and gauge the potential risks associated with reduced baseload capacity.

Appendix A: Scenarios and iterations

Table 12: Different iterations on Scenario 1

Planned Actions	Folder1	Folder1A	Folder1B	Folder1C
Belgium				
Historical production park	planned installed capacity	planned installed capacity	planned installed capacity	planned installed capacity
FeedIn	no	no	yes	yes
Fuel prices	constant	constant	constant	Estimated change
Loadfactor capacity renewables	constant	constant	constant	constant
Demand vector	estimated change	estimated change	estimated change	estimated change
Demand pattern	constant	constant	constant	constant
Analysed horizon	[2022, 2025, 2030, 2035]	[2022, 2025, 2030, 2035]	[2022, 2025, 2030, 2035]	[2022, 2025, 2030, 2035]
EU				
Historical production park	installed capacity in 2022	installed capacity in 2022	planned installed capacity	planned installed capacity
FeedIn	no	no	yes	yes
Fuel prices	constant	constant	constant	estimated change
Loadfactor capacity renewables	constant	constant	constant	constant
Demand vector	constant	estimated change	estimated change	estimated change
Demand pattern	constant	constant	constant	constant
Analysed horizon	[2022,2025, 2030, 2035]	[2022,2025, 2030, 2035]	[2022,2025, 2030, 2035]	[2022,2025, 2030, 2035]

[1] note 1: Full nuclear capacity in France is projected to be available starting from 2025 and beyond.

[2] note 2: The calculations made do not take into account any additional battery storage.

Table 13: Different iterations on Scenario 2

Net Zero Emission	Folder2	Folder2A	Folder2B	Folder2C
Belgium				
Historical production park	set to zero	planned renewables	set to zero	planned renewables
Renewable energy	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)
Storage	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)
Storage MWh	storage(tn) = 0	storage(tn) = 0	storage(tn) = 0	storage(tn) = 0
FeedIn	yes	yes	yes	yes
Transmission	constant	constant	allow investment (<20000MW)	allow investment (<20000MW)
Fuel prices	constant	constant	constant	constant
Loadfactor capacity	constant	constant	constant	constant
Demand vector	estimated change	estimated change	estimated change	estimated change
Demand pattern	constant	constant	constant	constant
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]	[2025, 2030, 2035]	[2025, 2030, 2035]
EU				
Historical production park	set to zero	planned renewables	set to zero	planned renewables
Renewable energy	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)
Storage	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)	allow investment (capacity = inf)
Storage MWh	storage(tn) = 0	storage(tn) = 0	storage(tn) = 0	storage(tn) = 0
FeedIn	yes	yes	yes	yes
Transmission	constant	constant	allow investment (<20000MW)	allow investment (<20000MW)
Fuel prices	constant	constant	constant	constant
Loadfactor capacity	constant	constant	constant	constant
Demand vector	estimated change	estimated change	estimated change	estimated change
Demand pattern	constant	constant	constant	constant
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]	[2025, 2030, 2035]	[2025, 2030, 2035]

[1] note 1: calculation started from 2025 onwards

Table 14: Different iterations on Scenario 3

SMR	Folder3	Folder3A
Combinations	**NZE + SMR**	**Planned Actions + SMR**
Belgium		
Historical production park	planned renewables	planned installed capacity
Renewable energy	allow investment (capacity = inf)	planned installed capacity
Storage	allow investment (capacity = inf)	-
Storage MWh	storage(tn) = 0	-
FeedIn	yes	yes
SMR	allow investment (capacity = inf)	substitution capacity
Transmission	constant	constant
Fuel prices	constant	estimated change
Loadfactor capacity	constant	constant
Demand vector	estimated change	estimated change
Demand pattern	constant	constant
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]
EU		
Historical production park	planned renewables	planned installed capacity
Renewable energy	allow investment (capacity = inf)	planned installed capacity
Storage	allow investment (capacity = inf)	-
Storage MWh	storage(tn) = 0	-
FeedIn	yes	yes
SMR	allow investment (capacity = inf)	-
Transmission	constant	constant
Fuel prices	constant	estimated change
Loadfactor capacity	constant	constant
Demand vector	estimated change	estimated change
Demand pattern	constant	constant
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]

[1] note 1: calculation started from 2025 onwards

[2] note 2: substitution for the CRM 2025 gas-fired-plants and nuclear extension

Table 15: Different iterations on Scenario 4

Gas Transition	Folder4	Folder4A
Combinations	**NZE + Gas**	**Planned Actions + Gas**
Belgium		
Historical production park	planned renewables	planned installed capacity
Renewable energy	allow investment (capacity = inf)	planned installed capacity
Storage	allow investment (capacity = inf)	-
Storage MWh	storage(tn) = 0	-
FeedIn	yes	yes
New Gas CCGT	allow investment (capacity = ∞)	substitution capacity
Transmission	constant	constant
Fuel prices	constant	estimated change
Loadfactor capacity	constant	constant
Demand vector	estimated change	estimated change
Demand pattern	constant	constant
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]
EU		
Historical production park	planned renewables	planned installed capacity
Renewable energy	allow investment (capacity = inf)	planned installed capacity
Storage	allow investment (capacity = inf)	-
Storage MWh	storage(tn) = 0	-
FeedIn	yes	yes
New Gas CCGT	allow investment (capacity = inf)	-
Transmission	constant	constant
Fuel prices	constant	estimated change
Loadfactor capacity	constant	constant
Demand vector	estimated change	estimated change
Demand pattern	constant	constant
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]

[1] note 1: calculation started from 2025 onwards

[2] note 2: substitution for the CRM 2025 gas-fired-plants and nuclear extension

Table 16: Different iterations on Scenario 5

Free Willy	Folder5	Folder5A
Belgium		
Historical production park	set to zero	set to zero
All technologies	allow investment (capacity = inf)	allow investment (capacity = inf)
FeedIn	yes	yes
Transmission	8000 MW	2000 MW
Fuel prices	estimated change	estimated change
Loadfactor capacity	constant	constant
Demand vector	estimated change	estimated change
Demand pattern	constant	constant
CO2 constraints	no	no
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]
EU		
Historical production park	planned installed capacity	planned installed capacity
All technologies	-	-
FeedIn	yes	yes
Transmission	yes	yes
Fuel prices	estimated change	estimated change
Loadfactor capacity	constant	constant
Demand vector	estimated change	estimated change
Demand pattern	constant	constant
CO2 constraints	no	no
Analysed horizon	[2025, 2030, 2035]	[2025, 2030, 2035]

[1] note 1: calculation started from 2025 onwards

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