DEPARTMENT OF ENGINEERING MANAGEMENT

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Kevin Milis, Magdalena Stüber, Johan Braet & Johan Springael

UNIVERSITY OF ANTWERP
Faculty of Business and Economics
City Campus
Prinsstraat 13, B.226
B-2000 Antwerp
Tel. +32 (0)3 265 40 32
www.uantwerpen.be

FACULTY OF BUSINESS AND ECONOMICS

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University of Antwerp, City Campus, Prinsstraat 13, B-2000 Antwerp, Belgium
Research Administration – room B.226
phone: (32) 3 265 40 32
e-mail: joeri.nys@uantwerpen.be

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A dispatching model based exploration of the post-nuclear phase-out Belgian energy mix

Kevin Milis *[2], Magdalena Stüber[1], Johan Braet[2,3], and Johan Springael[2]

[1]Chair of Renewable and Sustainable Energy Systems, Technical University of Munich
[2]Department of Engineering Management, University of Antwerp
[3]Department of Product Development, University of Antwerp

Abstract

While a possible nuclear phase-out for the Belgian energy system has long been the subject of both political and societal debate, prevailing government policy at the beginning of 2021 is to enact a full nuclear phase-out by 2025. While the Belgian government is committed to the phase-out, an evaluation moment is foreseen by the end of 2021, where the final decision on the prospective nuclear phase-out will be made. This is the backdrop against which this paper uses a dispatching model, based on the urbs modelling framework, to estimate possible post-phase-out Belgian energy mixes. The obtained results show an increased reliance on gas-fired plants, or, if CO_2 emissions are constrained to pre-phase-out levels, a marked increase in the amount of imported electricity and a fivefold increase in needed installed storage capacity. Total system costs increase as well, due to the additional storage required to allow for the increased penetration of renewable energy sources. These results show that there are important trade-offs between CO_2 emissions reductions, energy independence and energy system costs which will have to be navigated after the Belgian nuclear phase-out. Although not a priori part of the scope of the research, the results highlight several significant vectors for increased blackout risk, such as constrained electricity imports, the failure to realise the needed storage capacity explosion or transmission grid failures.

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*Corresponing author, kevin.milis@uantwerpen.be

Author Contributions

Contribution	Author
Design of the work	Kevin Milis, Magdalena Stüber
Data collection	Magdalena Stüber
Data analysis and interpretation	Kevin Milis, Magdalena Stüber
Drafting the article	Kevin Milis
Critical revision of the article	Kevin Milis, Magdalena Stüber, Johan Braet, Johan Springael
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1 Introduction

Nuclear energy has historically been an important contributor to the Belgian energy system: at the beginning of 2021, Belgium has 7 nuclear reactors, spread over 2 sites, with a total rated power output of 5 930 MW [1], providing around 50% of the total yearly electricity generation, ie. 43 524 GWh out of a total of 93 032 GWh electricity generated in 2019 [2]. Notwithstanding its important role in the Belgian energy system, the use of nuclear power has a long history of being the focal point of political debate: as early as 2003, legislation was put into place regulating the closure of the oldest Belgian nuclear reactors by 2015 [3]. However, this legislation was amended in 2013 and once again in 2015, with the closure of Belgium's nuclear reactors planned over the period 2022 to 2025.

When this nuclear phase-out was decided upon, the stated plan was that gas-fired power plans would be used as a transitionary measure until the Belgian electricity system is ready to be more fully powered by renewable energy sources, requiring both more renewable electricity generation as well as significant adaptations to the Belgian transmission and distribution networks. The viability of this strategy has however recently been called into question, as the Flemish regional government has been rather consistently refusing environmental permits for new gas fired power plants, citing concerns surrounding various emissions as primary reason [5].

Against that backdrop, this paper investigates possible future electricity energy mixes for Belgium, considering both total system cost and total emitted CO_2, with the goal to determine what feasible future electricity energy mixes are, from both technical and economic viewpoints. This paper uses the urbs modelling framework, developed at the Technical University of Munich [6]. Using this linear programming framework, various scenarios are evaluated based on their total system cost on the one hand and total CO_2 emissions on the other hand. The novelty of the approach used is that optimal dispatch models with an hourly resolution are used, as opposed to the more commonly used system adequacy models. The benefit of using an optimal dispatch model with an hourly resolution is that it calculates the system balance, i.e. energy produced equals energy consumed and losses, for each hour of the simulation, as opposed to the coarser granularity of system adequacy models, which often check energy amounts for an entire year. We argue that the optimal dispatch approach is more suited to evaluate energy systems that are characterised by a high penetration of non-dispatchable energy sources, such as electricity systems powered in part by renewable sources, as any hourly and seasonal imbalances between production and consumption are important, but risk becoming undetectable when the simulation is done at a coarser time-scale.

The next section provides more detail on the used framework as well as detailing the data-sources used and presents a detailed overview of the different simulations ran, while the third section discusses the outcomes of said simulations. The final section presents the conclusion.

2 Methods

2.1 Modelling framework

The work presented in this paper is based on the urbs framework [6], developed at the Chair of Renewable and Sustainable Energy Systems at the Technical University of Munich, and avaible online[1] under the GNU General Public License. It is a linear programming model, designed to handle multi-commodity and multi-site energy systems. urbs combines both investment decisions, adding or removing generation, transmission or storage capacity, and optimal dispatch decisions in the optimisation. Model inputs are specified in a spreadsheet file, while the actual optimisation is carried out using a third party solver, python is used for data input and output. Interested readers are referred to the documentation of urbs, freely available online, for a more in-depth discussion of the operation of the modeling tool.

urbs was used to model various scenarios, outlined in section 2.2, surrounding possible approaches to the make-up of the post-nuclear phase-out Belgian electricity generation park. All the simulations were ran to minimise the total system cost, comprising of the capital and operational costs, with total CO_2 emissions limited to a reference scenario, discussed below. Data on nuclear power production [7], the total system load for Belgium in 2018 [7] and the Belgian Energy mix [8] were obtained from Elia, the Belgian TSO[2]. Data for both wind power generation [9] and PV electricity generation [10] were sourced from Renewables.ninja[3]. The list of considered technologies include combined cycle gas turbines, nuclear power, offshore and onshore wind, solar pv, biomass and biogas, as well as energy recovered from waste.

[1]https://github.com/tum-ens/urbs
[2]All relevant figures and data reproduced with permission in this publication
[3]www.renewables.ninja

2.2 Simulations

Different simulations were ran, each investigating different scenarios for the post-nuclear phase-out Belgian electricity generation park. Each of the scenarios have in common that they were set-up to meet the historical demand for 2018 using a range of different generation technologies. The first of these scenarios is the *base* scenario. This *base* scenario serves the demand for 2018 using the historical generation park of 2018. This means that this scenario does not include investment decision, and the problem merely becomes optimal dispatch of the installed capacity. Not only does this scenario serve as a base of comparison for the other scenarios, it also serves as a tool for model validation, since the outcomes can be compared to published historical data for 2018. The *greenfield* scenario is the most open ended, as it starts without any pre-existing capacity, and as such gives an insight on the make up of the most economically efficient system configuration, based on the technologies available today, without excluding any possible technology. The scenarios *nuclear_out* and *nuclear_out_potential* closely resemble one another, as they both disallow the use of not only nuclear power, but any technology that emits CO_2. The difference between both scenarios being that *nuclear_out_potential* incorporates an additional restriction, in that the possible installable capacity of wind power is limited based on findings of Siala and Houmy [11], taking geophysical limitations on the available place for the installation of new wind turbines into account. *Nuclear_out_all*, lastly, again incorporates the phase-out of nuclear power generation, but also allows for non-renewable technologies to be installed as replacements for the lost generated nuclear power.

Based on the definition of the scenarios outlined above, spreadsheets containing all the necessary inputs where made[4]. Using the urbs framework, these inputs were converted into LP-problems, which were solved using Gurobi [12]. The resulting exact formulation of the objective function and constraints are outside the scope of this publication; an interested reader is referred to the urbs documentation [6] for more details. The output data[5] were then used as a basis for the reported figures and tables.

3 Results

Figure 1 shows the resulting power generated per generation type and the resulting CO_2 emissions for the first batch of simulations, across all scenarios. Two trends are immediately apparent, the first one being that across all scenarios, both gas and import are responsible for a larger share of the power generation

[4] Input spreadsheets are available upon request by contacting the corresponding author.

[5] Output spreadsheets are available upon request by contacting the corresponding author.

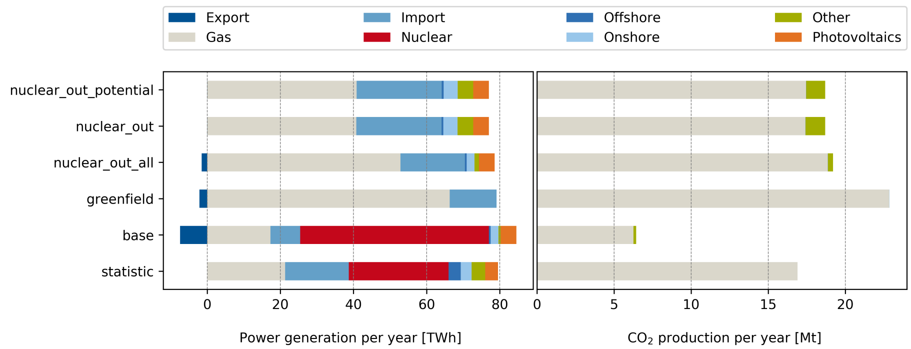


Figure 1: Power and CO_2 production across all scenarios, showing energy generated per source and resulting CO_2

per year, compared to the *base* scenario. This trend is most pronounced in the *greenfield* scenario, where only gas fired power plants and imported electricity are used to meet the total demand. It might seem counter-intuitive that the share of power generated by gas-fired power plants increases in the two scenarios that prohibit the installation of additional non-renewable generation, *nuclear_out_potential* and *nuclear_out*, but this is due to increased utilization of the existing capacity. Also of interest is that in all scenarios that build on the existing production park, little additional capacity of wind power or PV is added, but rather the solution that minimizes total system cost consists of only increasing capacity of dispatchable sources, such as gas fired power plants or electricity imports.

When the results for the *base* scenario are however compared to the available statistics, large discrepancies are noted, both in terms of sources of generated power as in CO_2 emissions. The discrepancy in power generation is in large part due to the fact that the *base* scenario was simulated with full utilization of all installed nuclear capacity, while in reality there was some downtime, both scheduled and unscheduled, in 2018. The large discrepancy between the emitted CO_2 amounts for the simulated base case and the actual emitted CO_2 amounts according to historical data is caused by the dearth of specific emission data on accurate emission factors for the Belgian generation park, which means that the emission factors used in the model are based on current best-in-class estimations, which are clearly a lot lower. While this means that that exact number of tons of CO_2 as calculated by the model is an under-estimation of reality, and not accurate, the difference between the various scenarios still allows for interesting comparisons. As figure 1 shows, all scenarios that phase-out nuclear power result in emissions that are between 3 and 4 times as high as the emissions of the base case. This shows that the Belgian government stated policy goal of achieving a nuclear phase-out might also have repercussions for another stated policy goal, namely reducing CO_2 emissions in line with Belgian engagements

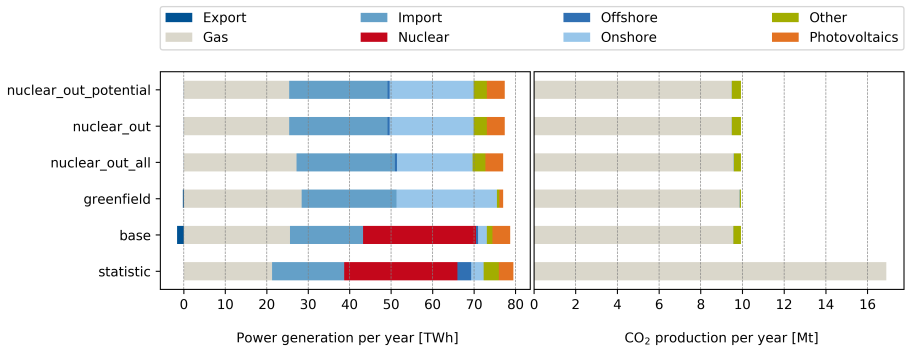


Figure 2: Power and CO_2 production across all scenarios, after rerun

outlined within the Paris climate protocols and COP26 agreements.

In order to remedy the concerns outlined above, the simulations were rerun with some modifications: the availability of the nuclear power plants was lowered to more closely match the historic availability, the total CO_2 emissions were limited to the total emissions of the base case as an additional constraint and, where available, the emission factors were updated. Figure 2 shows the results of these reruns. The addition of an emissions limit most heavily impacts gas fired power plants, as the large increases in power produced using this scenario that were visible in figure 1 are now no longer present; now onshore wind power and imported electricity are by far the most important energy sources to fill the gap left by the phase-out of nuclear power.

It is also interesting to note that the impact of updating the generation park data to 2020 or 2021 would be rather limited, as this would mainly increase the installed capacity of onshore and offshore wind power as well as solar PV, which would actually mean that the resulting system is even further away from the optimal solution, as the simulated results indicate that little extra intermittent generation capacity is added in any of the scenarios. This is made clearest when comparing the *base* scenario to the *greenfield* scenario: the *greenfield* scenario has less installed offshore and solar PV capacity than the *base* scenario. An increased renewable baseline capacity will therefore have a limited impact on the make-up of the electricity system, as gas fired power plants or imported power will still be needed as make-up power in large quantities, which will also become apparent as hourly results are discussed below.

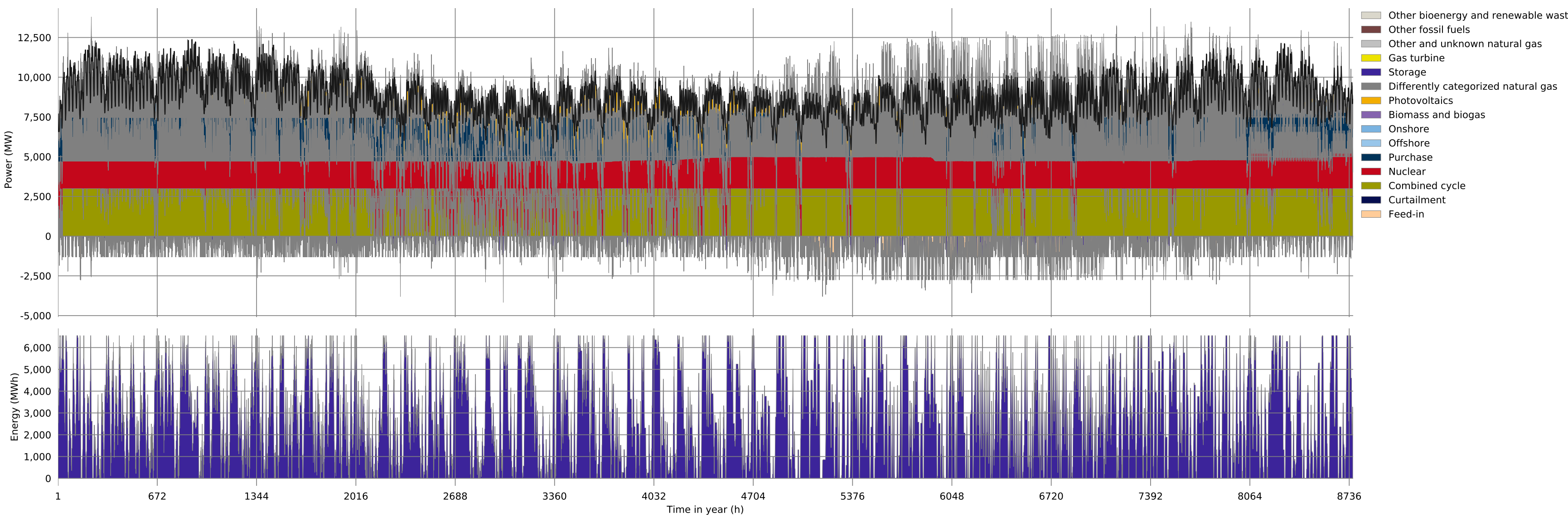
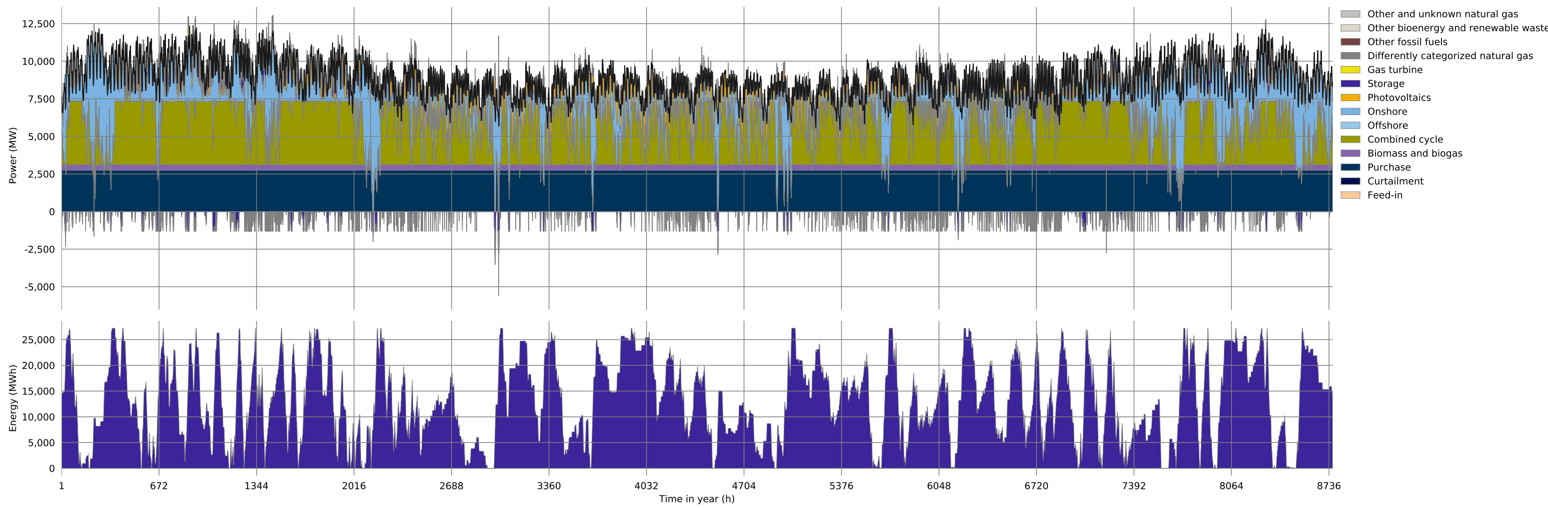
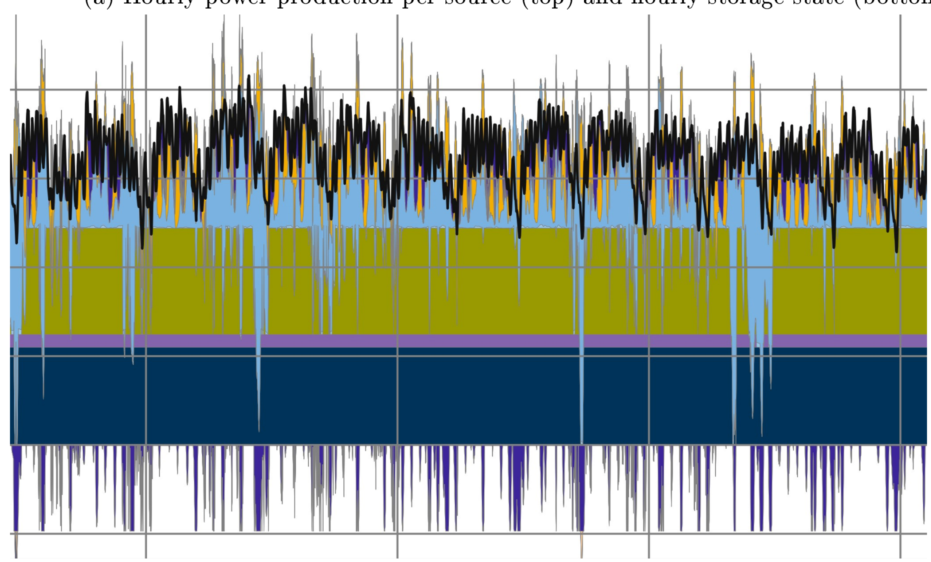


Figure 3: Hourly power production per source (top) and hourly storage state (bottom), for the *base* scenario



(a) Hourly power production per source (top) and hourly storage state (bottom)



(b) Zoom-in on four weeks during summer

Figure 4: Results for the *nuclear_out_all* scenario

Figures 3 and 4 provide further detail on the discussion outlined above[6]. Figure 3 shows the hourly results of the simulation of the *base* scenario, with the top half of the figure showing the power generated per energy source for each hour, and the bottom part showing how much energy is stored in the storage at that hour. Simply put, a nuclear phase-out means that the solid red band in figure 3 needs to be replaced, and figure 4a shows how this is accomplished in the *nuclear_out_all* scenario: by increasing the share of combined cycle generated power, as well as increasing power imports. Figure 4a also sheds more light on the intermittent and volatile nature of wind and solar power: while there are time periods where wind power alone is sufficient to serve the complete system load, these periods are few and far in between. Conversely, for a far greater amount of time the availability of wind power is limited, and the combination of import, biomass and biogass, and combined cycle needs to serve about three quarters of the system load. This also implies that sufficient installed capacity has to be available to meet these generation targets. When comparing the bottom halves of figures 3 and 4a, it is made clear that storage will play a far more important role after a nuclear phase- out: not only is the needed storage capacity more than quadrupled, from around 6 000 MWh to around 25 000 MWh, but the usage pattern is also different. In the *base* scenario, storage is mainly used to absorb short term fluctuations, as evidenced by the volatile pattern in the state of storage. After a nuclear phase-out however, storage is mainly used to counter fluctuations on a monthly scale.

Figure 4b provides looks in more detail at the usage of solar PV. In order to do so, it provides a look at four weeks in the summer, by zooming in on the relevant part of the data presented in figure 4a. The results clearly show that solar PV generated power is even more intermittent than wind power: while there is a more or less steady band of power generated by wind power, this is not the case for solar power, to some extend this is to be expected, as the sun does not shine at night.

It also bears mentioning that figures 1 and 2 are based on hourly time series for each of the individual scenarios -as presented in figures 3 and 4 for the *base* case and the *nuclear_out_all* scenario respectively- so while figures 1 and 2 might bear a superficial resemblance to the results of a system adequacy study, the method in which they are obtained is different, as the optimal dispatch model used in this work takes into account the hourly fluctuations of intermittent sources.

Table 1 shows the total system cost per scenario, with a similar caveat as for total CO_2 emissions: while these numbers are not necessarily accurate, they do give a clear insight into trends and differences between the various scenarios. Here, it is clear that any kind of phase-out scenario will result in an increase

[6]Higher resolution images are available upon request by contacting the corresponding author

Table 1: Total yearly system cost per scenario, in € Billion

Scenario	Operating cost	Investment cost
nuclear_out_potential	3.0	1.2
nuclear_out	3.0	1.2
nuclear_out_all	3.0	1.1
greenfield	2.8	2.1
base	3.2	0

of about one third in total system cost. This cost increase is mostly due to the cost for storage, related to the increased need for energy storage to support increased penetration of non-dispatchable, renewable energy generation. Furthermore, it might seem strange that the scenario with the least amount of constraints, the *greenfield* scenario, has the highest total system cost, the reason for this is however that this scenario can not benefit from older infrastructure, that has already been completely amortised, but can still be used.

The presented results come with some limitations, however. As was discussed previously, not all technical data surrounding generation is publicly available; as is the case of all modelling and simulation endeavours, the quality of available input data directly impacts the reliability of the obtained results. Secondly, the simulations could be enhanced by integrating a geographical component: not only will the nuclear phase-out entail a switch in energy source, but also the location where this energy is generated will change: consider for example the chemical cluster located in the port of Antwerp, it is currently almost co-located with the four nuclear power reactors on the site of Doel, but will in future need to be served with increasing amounts of wind power, coming from either more rural areas, or from off-shore locations in the North Sea. As a result, the reported systems costs are an underestimation of of the real costs, since transmission related effects are not yet taken into account. It is critical to note at this juncture that these system integration costs are expected to be significant, Ueckerdt et al.[13] estimate that the integration cost of wind energy at high penetration levels will be of the same order of magnitude as the generation costs. In order to estimate these impacts, the model needs to be expanded to include transmission effects.

While the discrepancy between the modelled and historical outcomes for 2018 might indicate that there are also other considerations beyond cost minimisation which impact the operation of the Belgian electricity system, cost minimisation still remains a valid objective, and the comparisons between different scenarios reveal system behaviours and trends that are worthwhile to discuss. Furthermore, while these confounding considerations will mean that the modelled result will always deviate from the realised outcome, a cost-minimizing model means that it is possible to estimate the cost to society from serving these other considerations.

Notwithstanding the limitations outlined above, the simulations show a clear increasing dependency on import of electricity, which, while seemingly both economically and ecologically advantageous, we would argue is problematic: not only would this mean an increasing dependence on foreign nations to meet our energy needs, this strategy of increasing reliance on electricity imports can only work as long as it does not become a dominant strategy among European countries, for obvious reasons.

The findings presented in this work contrast with the results presented by Energyville [14]: based on a system adequacy study, Energyville reported an expected share of around 50% of belgian electricity generation to be based on renewables by 2030. It is however not clear how much additional storage is needed to enable this, and whether the resultant costs are included. The Energyville results do match up with the results of this study where the increased need for gas-fired power generation is concerned. The results of this work more closely match those of Kunsch [15], who also used a dispatching model to evaluate the results of a nuclear phase-out for Belgium, as Kunsch notes that there will be a high need for imported electricity, and even goes so far as to state that any closure of nuclear power plants will endanger the security of supply.

While the simulations highlight the choices and trade-offs that will need to be made to successfully phase-out nuclear power generation in Belgium, it is important to note that the simulations were only concerned with meeting historic demand. There are several trends and policies which have the expected effect of increasing electricity demand in the mean term, such as the switch to electrical vehicles, switching from natural gas heating to heat-pump based heating, or ever increasing ICT-usage. Although an estimation of the size of these increases is beyond the scope of this paper, it is obvious that any sizeable increase in demand will only exacerbate any worries or problems surrounding security of supply.

Blackouts were not included in the modelled possible outcomes, and the models seem therefore to indicate that all load can be met at all possible times. This 'no blackout' outcome is contingent on the important but tacit assumption that large quantities of imported electricity are available. While this problem has never historically occurred, not only has been a rather close shave in the winter of 2018-2019, looking at the significantly increased electricity imports forecast by the model, one may strongly question the validity of this limitless availability of imported electricity.

Additionally, the phase-out scenarios are all dependent on the installation of extra storage in order to absorb the intermittent production of the installed renewable electricity sources. It should be noted that the model estimates that storage capacity will need to be sharply increased, from 6 000 MWh currently, to 25 000 MWh. While the model results indicate that this increase is economically feasible – and needed in order to avoid blackouts – it is questionable how realistic such a large expansion is: the used cost technical parameters are for the pump storage facility at Coo, and it is highly unlikely that it is possible to almost quintuple the capacity of the water reservoir in two to three years. Another option are utility scale battery systems, but given the required capacity, implanting this amount of battery storage without undue backlash of local communities will probably prove to be non-trivial.

Although a full evaluation of the effects of a nuclear phase-out on the transmission grid is out of scope for this paper, the results nevertheless indicate at least a shift in how the transmission system will be used, as the electricity system will transform from a grid that is centrally fed by comparatively few but large sources into one that is decentrally fed by many smaller generation sources. It stands to reason that this will pose significant challenges for the transmission grid and will more than likely require sizeable investments in order to facilitate the resultant power flows, with magnitudes and directions the current transmission system was never designed to handle. It is therefore strongly recommended that further studies are commissioned which take these transmission effects into account, as this inclusion will most probably impact both the overall system costs as well as system stability.

Apart from the previously highlighted supply shortage blackouts the large projected shifts in energy mix, towards imports and decentral generation, also increase the risk for transmission failure related blackouts, unless measures are undertaken to significantly strengthen the transmission grid. While the topic of blackouts is not in the scope of the work carried out, the obtained results show big departures from the established mode of operation of the Belgian grid, which indicates that blackout risk after the nuclear phase-out merits serious study. As such, further refined models which are able to more closely mimic historic data, incorporating the transmission system, and reasonable and realistic limits on both electricity imports and storage capacity expansion are valuable avenues of further research, and vital in ensuring continuity of electricity supply to Belgian homes and businesses.

4 Conclusion

The linear optimisation framework urbs was used to simulate different scenarios for the electricity mix of post-nuclear phase-out in Belgium. Results show that such a phase-out will mean either a tripling or quadrupling in CO_2 emissions, or an increase of one third in yearly total system costs combined with a heavy reliance on electricity imports. Furthermore, these cost estimates do not take the effects on the transmission grid of a phase-out into account, which means that even more investment than calculated will be required to forestall blackouts. While the energy mix is a societal and political choice – on which even the authors do not share the same opinion – the presented results indicate that a nuclear phase-out in the current Belgian situation is not desirable. Additionally, these findings are only based on meeting the historical load; with expected increasing future electricity loads, this highlights the need for a decisive, realistic and future-proof Belgian electricity policy. Furthermore, the model results show that there is more work needed to accurately model the impact of the increased projected renewable penetration on the transmission grid stability and blackout risk, as well as investigating the black-out risks surrounding high dependence on imported electricity.

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