

Not if, but when? Simulating the impact of timing the nuclear phase-out in Switzerland

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Abstract

Swiss electricity companies are faced with uncertainty with regards to the future operation of nuclear power plants in the country. After Fukushima in 2011, the government decided on a gradual phase-out, but only provided a tentative planning. Hence, no new nuclear power plants can be constructed but the old power plants will be allowed to operate until they are no longer deemed safe by the nuclear regulator ENSI. However, the first of the five Swiss nuclear reactors will shut down in 2019, following a decision of the owner, not ENSI, three years ahead of the government's original schedule. Recent efforts by politicians and citizens to fix the date of the phase-out were unsuccessful. In this paper, we look at the effect of the timing of the phase-out and the associated uncertainty on the wider electricity market. More specifically, we look at the impact on investments, security of supply, wholesale electricity prices, and the amount of greenhouse gas emissions. We developed a simulation model using system dynamics to increase our understanding of the Swiss nuclear phase-out. The system dynamics model includes modules for merit order dispatch, international trading, investment analysis, generation capacity expansion, hydropower storage and dispatch, and other renewable energy production. The model is calibrated with data of the Swiss energy system and includes anticipated policy changes of the wider energy transition in Switzerland. Preliminary results, using various scenarios of both timed and untimed nuclear phase-outs with varying levels of uncertainty, show that the timing uncertainty does not significantly impact market development. Investors seem to wait for observable rather than anticipated market changes. However, delaying the nuclear phase-out does have significant advantages in terms of greenhouse gas emissions and security of supply. The implications of these findings are discussed in the context of the Swiss Energy Strategy 2050 and the country's obligations under the Paris Agreement.

Key Words

Electricity market, investment, security, energy transition, system dynamics, simulation, Switzerland, nuclear phase-out, uncertainty

Introduction

Switzerland has committed to a challenging transformation of its energy supply infrastructure. The alpine federation is currently relying on domestic nuclear power for slightly over a third of its electricity supply¹, the remaining two thirds supplied by hydropower and a small fraction by waste incineration and new renewables such as wind and solar. After the Fukushima accident in 2011, Switzerland decided to cease granting permits for new nuclear power plants, effecting a gradual nuclear phase-out in the near future as Switzerland's five nuclear reactors represent the oldest fleet of nuclear power plants in the world². This decision was recently reaffirmed by popular vote, which simultaneously pushed forward the development of new renewables and energy efficiency as the solution to the future gap in power supply³. However, the development of alternative supply in the form of new renewables is facing many problems in Switzerland: social acceptance⁴, low potential⁵, low economic attractiveness⁶, and a high policy risk⁷, all possibly leading to investor reluctance. Electricity imports can provide temporary relief. However, Switzerland's overall objective is to remain relatively self-providing and the cross-border transmission capacity is already showing signs of congestion due to Switzerland's central location for inter-European trading⁸. Expansion of domestic fossil fuel power plants such as natural gas would very likely result in large public opposition as well as potential conflicts with the Swiss obligations under the Paris Accord, aiming to reduce greenhouse gas emissions by 50% by 2050⁹.

It is clear that the decision to phase out nuclear energy brings a large amount of uncertainty to the forefront of an already troubled electricity industry. Although the country is bound by the phase-out, it is not bound by a schedule. A recent popular vote to limit the lifetime of the existing nuclear power plants to 45 years and effectively provide a schedule was rejected¹⁰. The fleet of power plants was originally built to last 30 years, but the expectation is that they will manage to be safely operated for 50 years or longer. Power plants and other electricity infrastructure take several years to construct¹¹. Without a schedule, the market is given little prior warning, making it hard to build a replacement source of electricity supply in time after the decision has been made to shut down a reactor. Temporary supply shortages can lead to price spikes, system instability, and security of supply issues.

A model of the Swiss electricity system based on System Dynamics was made to explore the impact of this uncertainty on the electricity system and Swiss obligations under the Paris Agreement. Specifically, we look at the length of the notice period for each nuclear reactor's shutdown and the impact on investments, security of supply, wholesale electricity prices and the amount of greenhouse gas emissions. The results will indicate whether providing more clarity to the market players will be overall beneficial.

Methodology

Long-term energy system models can be broadly categorized into three groups: equilibrium models, optimization models, and simulation models¹². Equilibrium models assume that rational actors interact under rules of perfect competition in such a way that equilibrium prices are reached. An electricity system in transition entails significant system delays and actors have imperfect information and is thus clearly out of equilibrium, as many researchers have shown^{13–15}.

Optimization models assume perfect foresight and a single, omniscient planner to direct the evolution of the system based on cost minimization or some other optimization criteria. Even the most sophisticated constrained optimization models do not forego that basic assumption, which makes them unsuited to explore the question of bounded rationality, imperfect competition and time delays in this study.

Simulation models, which include a range of options including bottom-up approaches such as agent-based modeling and top-down approaches like system dynamics, are better suited to model electricity markets under these conditions¹⁶. We chose system dynamics because we are concerned with system-level impacts of the uncertainty surrounding the nuclear phase-out. System dynamics can adequately deal with long-term feedback, time delays, bounded rationality, and imperfect information¹⁶, necessary for adequately exploring our research topic.

Model description

The model was created on the Vensim[®] DSS for Windows 6.4E software platform. It is an extension of earlier work at EPFL^{17,18}. The additions made to the model for this study include carbon dioxide emissions, a variable notice of each reactor's planned shutdown (*investor foresight*) and additional phase-out schedules. A brief introduction to the model follows below. For a more detailed explanation of the model, including verification and calibration steps, we refer back to our previous work.

The model simulates the Swiss electricity system between 2015 and 2050, aligning with the Energy Strategy 2050 and allowing sufficient time to explore long-term problems. The model has an hourly resolution, unlike other models of the Swiss market which have used months or representative days in order to cut back on simulation time^{19,20}. An hourly resolution is necessary to explore system instability and price spikes, as these are not expected to happen on representative or average days but rather on those exceptional days when multiple factors concur, e.g. unfortunate weather, maintenance schedules, network congestion, or high demand.

The system dynamics model centers on the spot market and merit order dispatch (Figure 1), but also includes modules for international trading, investment analysis, generation capacity expansion, hydropower storage and dispatch, and other renewable energy production. Merit order dispatch is based on marginal costs of the generation technologies^{11,20,21}. The exception is hydropower, both pumped storage and regular, of which the bidding prices are based on opportunity costs, reflecting the ability of operators to plan the use of their resources strategically²². Opportunity costs are inversely related to the availability of water, scaling in relation to the market prices and marginal prices of alternatives in a similar fashion as other studies^{23,20}. Hydropower pumped storage and international trading are performed in a similar fashion, comparing spot prices with available capacity¹ and trading or pumping whenever deemed profitable. These transactions happen ex-ante, i.e. before the market is cleared, thus reducing the residual demand. A part of the international trade is also done via long-term bilateral contracts, notably fixed-price call options with France²⁵. These function in the merit order in the same way as domestic dispatchable power but also reduce the available NTC for spot trading with France when utilized.

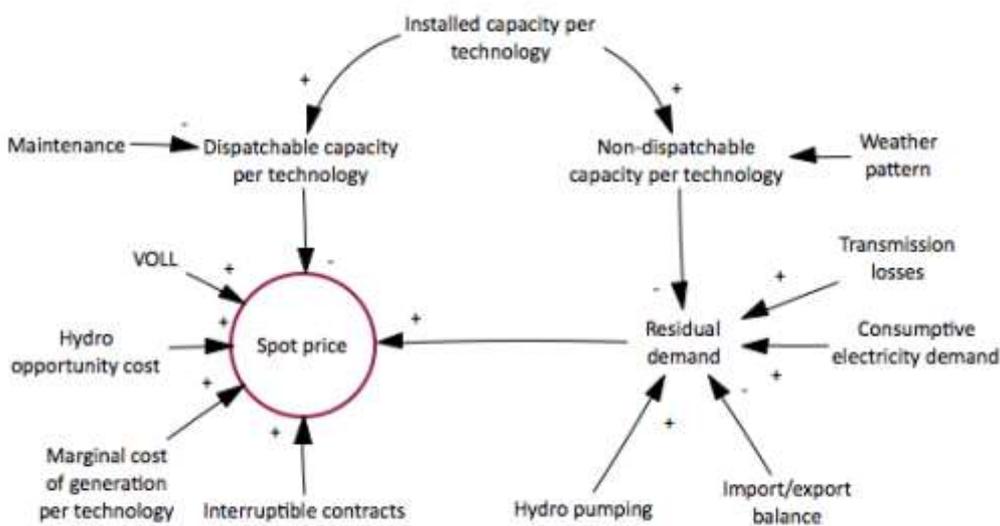


Figure 1: Conceptual overview of the spot market and merit order dispatch.

The model uses several exogenous inputs. Foreign spot prices are taken as exogenous and modeled using 2010-2014 data from EPEX² and GME to generate hourly profiles, combined with ENTSO-E future projections²⁴. Consumptive demand growth is implemented using projections taken from the VSE, the Association of Swiss Electric Companies¹¹, coupled with standardized hourly profiles generated from Swissgrid data³. This means the model does not explicitly take into account possible changes to demand patterns due to e.g. electric vehicle charging or price elasticity²⁶. Weather patterns are similarly created from historical data and future projections and impact weather-dependent parts of the model such as run-of-river and reservoir inflow^{4,11}, wind^{5,27}, and solar²⁸.

The model also includes a module for investment analysis and project development (Figure 2). The project pipeline traces each project from permit application through approval, construction, operation and decommissioning and is based on the work of Vogstad²³. There are two decision points for investors based on the investment analysis. The first is at the permit application stage. After the permit has been

¹ Pumping availability based on actual reservoir modeling. Hourly Net Transfer Capacities (NTC) for each neighboring country calculated using future projects of the ENTSO-E²⁴ and historical data for hourly patterns:

https://transparency.entsoe.eu/content/static_content/Static%20content/Legacy%20data/year%20selection.html

² <http://www.epexspot.com/en/market-data/dayaheadauction/auction-table/>

³ https://www.swissgrid.ch/swissgrid/en/home/experts/topics/energy_data_ch.html

⁴ http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=en&dossier_id=00767

⁵ <https://www7.ncdc.noaa.gov/CDO/cdo>

approved, the project comes into a stock of approved projects and will only start construction after an investor decides to go forward with the project. If this takes too long, the building permit can also expire.

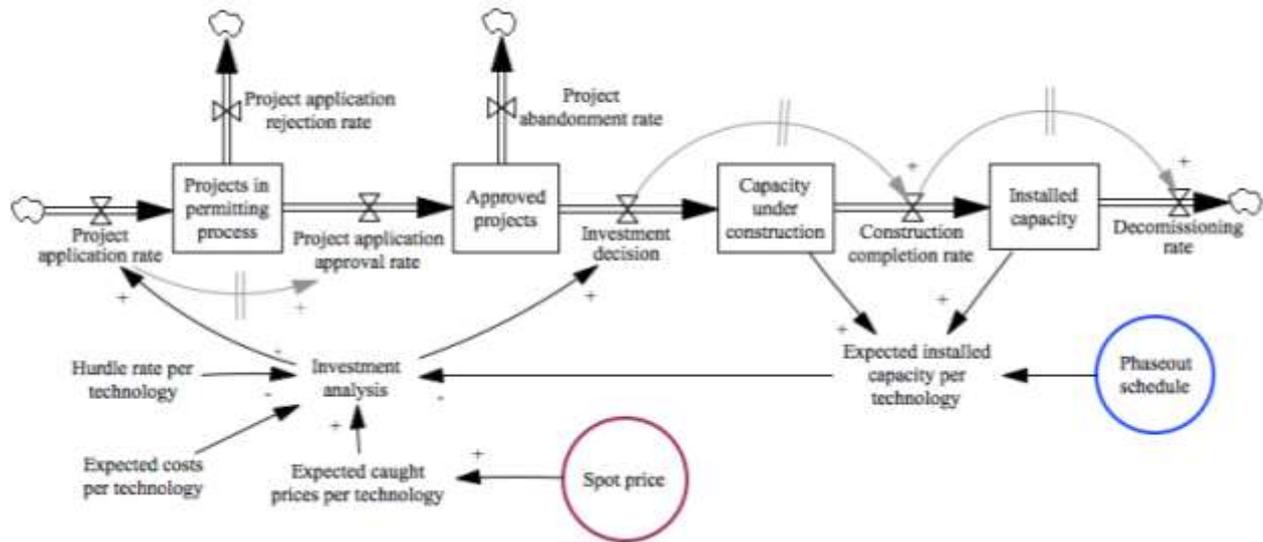


Figure 2: Conceptual overview of investment analysis and project development.

Investment analysis is done by estimating a project's IRR and comparing to a corporate hurdle rate¹¹. This is a proven way to model investor behavior which many other researchers have taken in similar works as well^{14,15,29,30}. Inputs for IRR calculation are plagued by bounded rationality – investors do not have perfect foresight and base their decision on the information available to them and their expectations on the future state of the system. Investors are made aware of each nuclear reactor's shutdown 1 to 6 years in advance, allowing them to plan accordingly. Since the delays associated with building power plants range between 1 to 4 years depending on the technology¹¹, this may or may not be enough time to build sufficient new generation capacity. The decommissioning of Mühleberg, which is the first reactor to shut down, planned for 2019, was announced 3 years in advance by the operator due to economic reasons³¹, and not by the nuclear regulator ENSI due to safety concerns. Should the ENSI detect safety concerns and force the reactor to shut down, the notice would likely be shorter than 3 years.

Endogenous investments are made for solar power, wind power, and combined cycle natural gas turbines (CCGT) using cost structures including carbon prices and learning curves from the VSE¹¹ and subsidy schemes as currently in place and planned in Switzerland. Investments in other power generation options, notably hydropower, are taken as exogenous¹¹. This is done because other investments options are prohibited (i.e. nuclear), marginal (e.g. geothermal), or already exploited to their maximum potential (e.g. hydropower, waste to energy), and their respective impacts are therefore strongly limited. Investors only incorporate the projects that are under construction in their investment decisions and no permit applications or approved projects by other investors as these are not definitive yet.

Results

The model contains over 600 variables and we analyzed over ten thousand different scenario combinations, thus it is impossible to discuss all of our findings. This section will only highlight the most relevant findings with regards to the uncertainty surrounding the nuclear phase-out. Most findings will be supported by visual evidence, but some findings will only be discussed in-text.

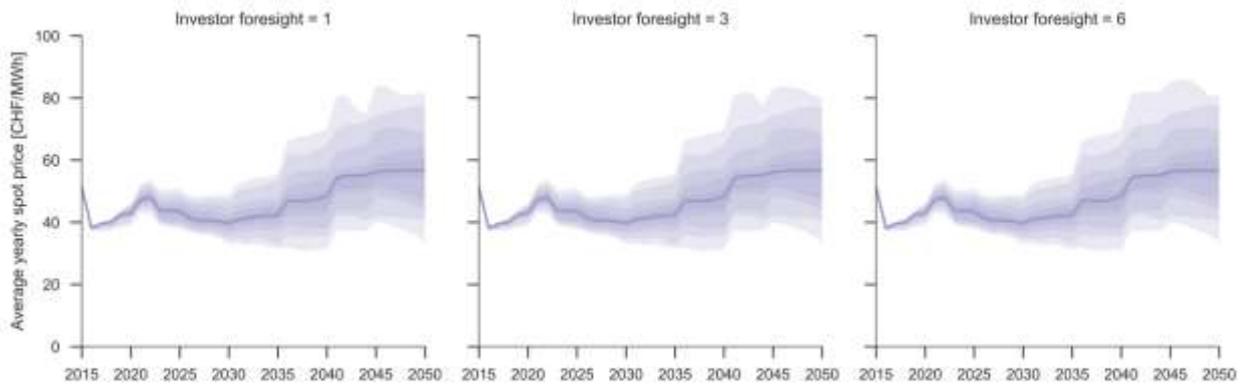


Figure 3: Yearly average spot price when investors are given 1 (left), 3 (middle), 6 (right) years of notice.

The first insight from Figure 3 above shows that Swiss electricity prices will most likely remain depressed, fluctuating at or around 50 CHF/MWh, for at least the coming 10 years. Averaged over the coming half-century, we can observe a slow positive trend in electricity prices. Although the uncertainty grows exponentially in electricity price forecasting, we find that nearing 2050, spot prices will most likely be in the range of 50-90 CHF/MWh. However, these prices are largely dependent on domestic demand developments (Figure 4). The simulation uses three different demand scenarios, one where electricity demand growth stabilizes and starts to decline, another where demand simply stabilizes and one final where demand keeps growing (although at an increasingly smaller rate). Electricity prices in the growing demand scenario are roughly a third higher than in the declining demand scenario (Figure 4). It cannot be said with high certainty how electricity demand will develop. There are strong domestic, and global, efforts to reduce consumption and increase efficiency on the one hand, but on the other hand an electrification of heating and mobility is anticipated as well. Nonetheless, we deem a medium or growing demand scenario as most likely, in light of the Energy Strategy 2050 which both stimulates electrification of heating and transport, as well as an increase in energy efficiency³.

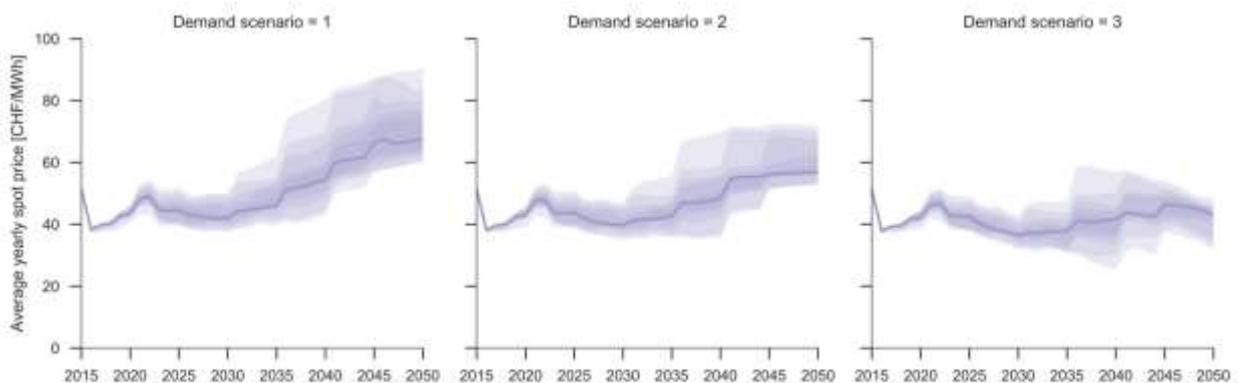


Figure 4: Yearly average spot price in simulations with growing (left), stabilizing (middle), and declining (right) demand.

The second reason could be that investors would change their CCGT investment behavior, but there are no investments in CCGT power plants hence there are no differences. If we look at only the scenarios where demand keeps growing the coming decades, some CCGT power plants are built, we observe a slightly more differentiated pattern than in Figure 3 but the differences remain negligible. From this we can conclude that timing the nuclear phase-out earlier in advance will probably not impact the electricity market development, and little risk is posed by allowing the nuclear regulator ENSI decide each shutdown ad-hoc.

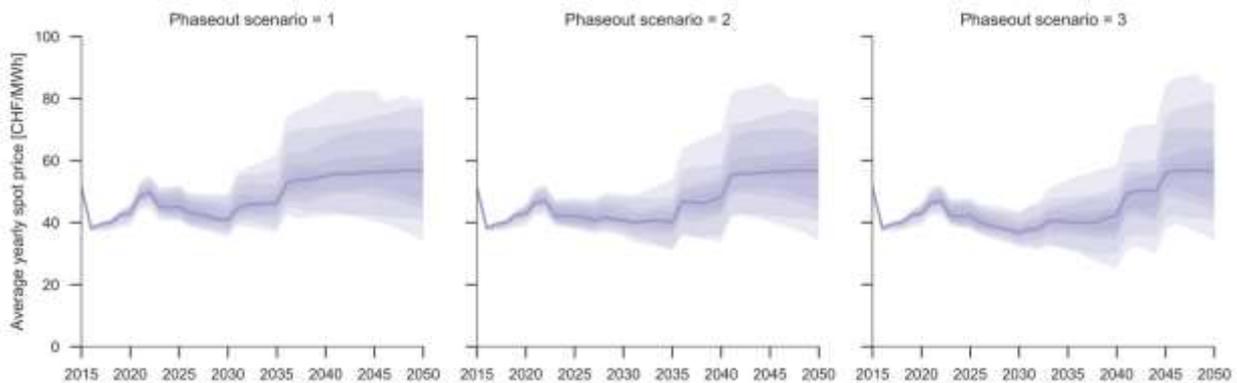


Figure 5: Yearly average spot price when nuclear power plants have an average 50 (left), 55 (middle), and 60 (right) years of lifetime.

However, another factor remains, and that is the average lifetime of each nuclear power plant. In Figure 5 above, we find in those instances where the lifetime of the nuclear power plants is extended further than the 50 years originally anticipated in 2011 by the Swiss Federal Office of Energy³², that an eventual electricity price increase is similarly postponed. This is not unexpected, as less investments have to be made and the marginal costs of operating nuclear power plants are incredibly low compared to most other generation options. The figure suggests that the electricity market will develop differently depending on the eventual nuclear phase-out path. What is most relevant to see is whether this change will have an impact on security of supply and on the eventual amount of greenhouse gas emissions.

Looking at additive power-related CO₂ emissions in Figure 6, we find that emissions are likely mildly lower by the end of the half-century if the phase-out is delayed. We postulate two logical reasons for this. Firstly, the fact that lower average electricity prices persist makes it harder for CCGT to compete. Secondly, and perhaps more intuitive, is that the possible supply gap due to the phase-out is postponed and it is much harder for CCGT power plants to compete in the future, where solar and wind are expected to be much more competitive than they currently are due to learning effects and cost reductions.

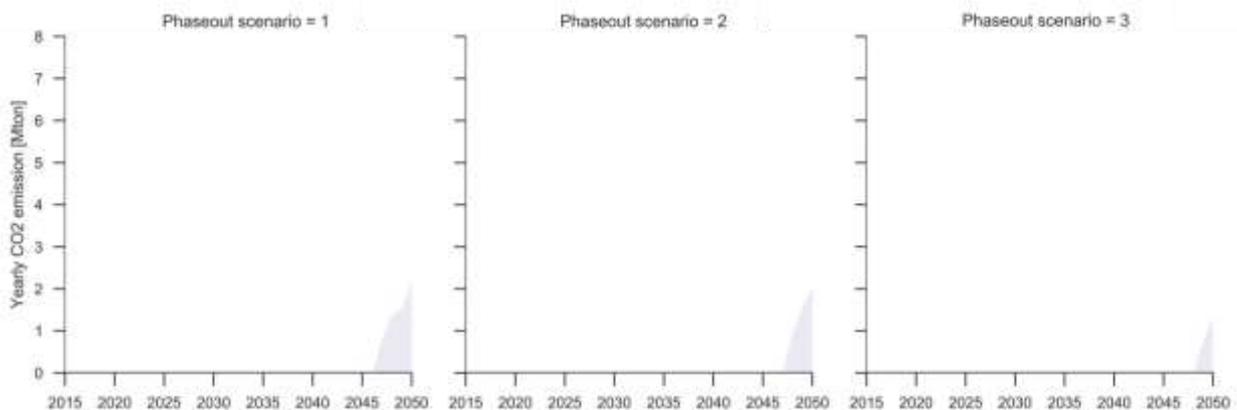


Figure 6: Additive yearly CO₂ emissions compared to 2015 with a growing NTC capacity and when nuclear power plants have an average 50 (left), 55 (middle), and 60 (right) years of lifetime.

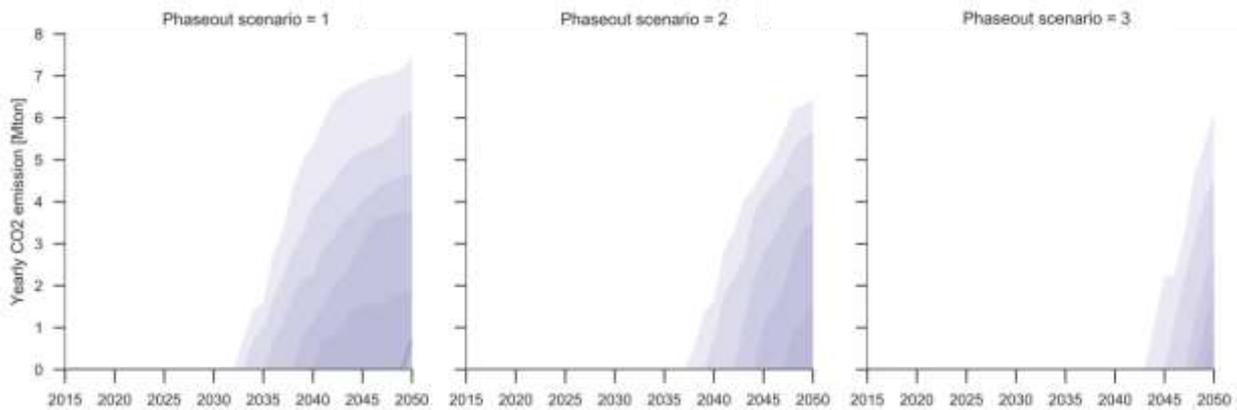


Figure 7: Additive yearly CO2 emissions compared to 2015 with a constant NTC capacity and when nuclear power plants have an average 50 (left), 55 (middle), and 60 (right) years of lifetime.

However, this difference becomes significantly more pronounced when plotting the same figures while *not* allowing for cross-border trading capacity to expand following the TYNDP of the ENTSO-E²⁴, as we have done in all previous graphs, but rather keeping them at their current value (Figure 7). Investments into CCGT are then strictly necessary as there is not enough availability to import electricity. Greenhouse gas emissions grow significantly, potentially reaching heights of up to 7 MT CO₂ per year, approximately 13% of the Kyoto 1990 baseline for Switzerland³³. In essence, this is what will be necessary if Switzerland does not want to expand its import dependency and keep their electricity supply locally generated. We find this effect to be the strongest when domestic electricity demand is growing, mild when demand growth stabilizes, and disappearing altogether when demand can be reduced from today's situation. This shows the importance of curbing electricity demand growth. Simultaneously it shows the inherent risk entailed by aggressively electrifying heating and mobility services, namely that it will merely shift emissions to the power generation sector.

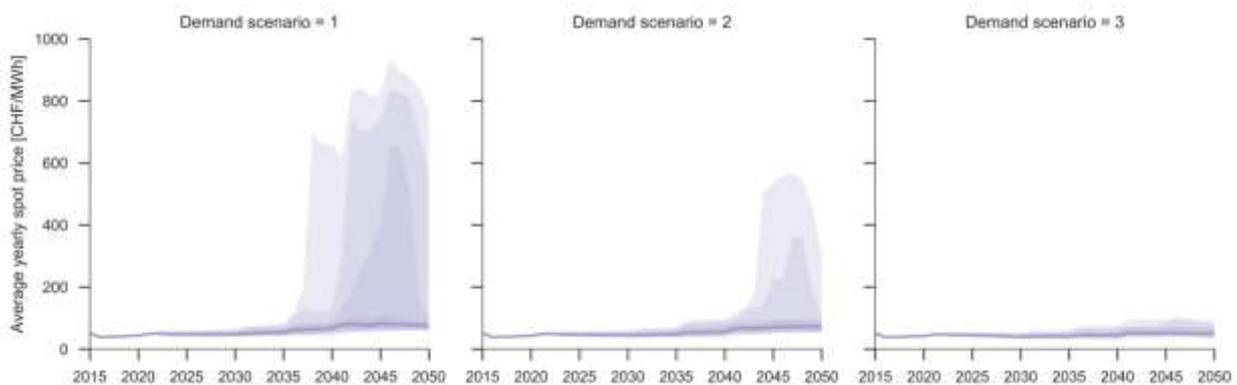


Figure 8: Yearly average spot prices in simulations with a constant NTC capacity and growing (left), stabilizing (middle), and declining (right) demand.

Greenhouse gas emissions are not the only important indicator of the market development. The security of power supply is crucial too. Power shortages, even if they last relatively short, pose an incredibly high risk to the Swiss economy, potentially causing billions of CHF in damages³⁴. Figure 8 illustrates the development of the security of supply. Note the change of axis with respect to the previous figures. High electricity prices signal scarcity and a high risk for blackouts. The risk completely disappears when demand is declining (right). The risk also completely disappears when the NTC is developed according to the ENTSO-E plan, as seen in Figure 3 and Figure 5.

Discussion and conclusion

Switzerland decided to phase-out of nuclear energy in 2011 after the nuclear fallout in Fukushima and reaffirmed this position by popular vote in 2017. The chosen phase-out pathway is marked by high levels of uncertainty for investors and potential risks to the security of supply as nuclear is currently an integral part of its supply. Swiss commitments to reduce carbon emission under the Paris Accord further complicate the transition. Unique for the case of Switzerland is the already low amount of carbon emissions associated with power production, currently a combination of nuclear and hydropower. Switzerland does not currently have any fossil fuel power generation, meaning most emission reductions will have to come from other sectors such as mobility and heating, undoubtedly necessitating a further electrification for both.

To investigate these matters, we developed a system dynamics model of the Swiss electricity system, including the spot market based on an hourly merit order, new investments in CCGT, wind, and solar, international trading, and hydropower reservoirs and strategic bidding. We used this model to investigate the impact of the uncertainty surrounding the phase-out on the Swiss electricity market and greenhouse gas emissions. The model estimates the CO₂ emissions per year from newly built CCGT plants, and thus represents the additional burden of CO₂ reductions that Switzerland will have to capture, offset or reduce in other parts of their economy in order to meet the emission reduction targets.

Our results show a clear trade-off between increasing the dependence on electricity imports and the domestic development of natural gas-fired power plants in order to keep the security of supply sufficiently high. If the nuclear phase-out is delayed, or if demand can be significantly curbed with respect to today's levels, this trade-off becomes less strong. Under current UNFCCC rules, the carbon emissions from imported electricity do not count as domestic emissions, and hence it would be easier for Switzerland to meet its greenhouse gas reduction targets by increasing their cross-border trading capacity rather than domestic generation. We found that the amounts of greenhouse gas emissions from newly built CCGT power plants can reach heights of 7 million tons per year, about 13% of the 1990 Kyoto baseline for Switzerland³³. This would mean a huge amount of emissions need to be captured or elsewhere abated to reach the climate goal of 50% fewer emissions in comparison to this baseline. However, domestic power plants are a more reliable supply option than electricity imports, where cross-border congestion can mean supply issues for Switzerland if the dependence becomes too high. Several simulations have shown power shortages as a result of an excessive dependence on imports in winter. Our results also showed that timing the nuclear phase-out further in advance does not significantly impact the market development. Investors seem to wait for actual market changes rather than anticipated changes. Thus, we identify no inherent risk to allowing the nuclear regulator ENSI decide each reactor's decommissioning on an ad-hoc basis. However, the lifetime of the nuclear power plants was found to be more important. We can clearly see that the chosen phase-out pathway in Switzerland, where the nuclear power plants are allowed to operate for an undetermined time period but cannot be replaced, has both upsides and downsides. Nuclear provides stability in the Swiss electricity market for now, which is hard to replace solely by renewables such as solar and wind. A strong dependency on imports will be the most likely result, which will mean a lower security of supply in Switzerland overall. If demand growth can be curbed this trade-off will be much smaller and the transition objectives in the Paris Accord and the Energy Strategy 2050 will be more easily and securely met.

We identify a few limitations to our analysis. First, the system boundaries are set at such that only domestic affairs are taken into account. The assumption is that the electricity markets in the much larger countries France, Italy and Germany will not be influenced significantly by the developments within Switzerland. Investments in cross-border transmission capacity are similarly exogenous, which can have an impact on the findings given the importance of imports and cross-border congestion to the security of supply in certain scenarios. Second, we use standardized hourly demand profiles, meaning that the seasonal and hourly load distribution is kept constant throughout the simulation. Any impact the

electrification of services will have on the relative timing of the demand peak, e.g. with regard to the seasons or daily solar pattern, is not included. This can have an influence on the viability of hydropower, storage, and solar technologies, as well as the market evolution in general. Third, system dynamics aggregates all power plants of each technology into a single stock, meaning there are no individual ramping constraints and marginal costs for individual power plants. Fourth, the entire market is represented by the spot market, meaning the futures and day-ahead markets are not included. The spot market is more volatile and this can be reflected in the results. Lastly, it has proven incredibly difficult to predict the developments of the costs of renewables in the long term. The investment behavior and electricity market might change substantially if the developments differ from the projections used in this model.

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