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Dissertation summary

Efficient decarbonisation of competitive electricity markets

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1 Subject and objective of dissertation

Deregulation of electricity markets and technological progress of renewable energy generation technologies have challenged many of the assumptions underlying capacity expansion planning problems. Methods and tools that have been successful in the past are becoming increasingly unfit to handle newfound uncertainty, whether it is due to competitive market pressure or mechanisms internalising externalities.

The primary objective of the dissertation is to validate

1. the efficiency of carbon dioxide internalisation mechanisms on the electricity markets in reducing CO_2 emissions from existing installations and reshaping capacity mix of power systems to low-carbon sources.

The supplementary objective is to verify the following:

2. feasibility of running conventional power system with extremely high penetration level of renewable energy sources (RES),

3. substantial interdependency of mechanisms for decarbonisation and those fostering expansion of renewables in the power systems, to the point of complete mutual substitution,

4. significantly higher power system costs in Poland resulting from either decarbonising or fostering renewables growth, compared to baseline business-as-usual scenario.

The supplementary hypotheses can be perceived as alternative framing of the main thesis. The second thesis explores additional underlying assumption, under which decarbonisation can be viewed as replacing conventional fossil fuel power mix with renewables. Following from that assumption, one could argue that power systems dominated by erratic renewables production are technically unfit to cover variable demand for electricity. I challenge that belief by constructing a feasible, if challenging, power system capacity expansion plan with 80% share of renewables in the system in 2030, going far beyond the current political and environmental ambitions.

The third thesis goes deeper into researching interactions of decarbonisation and renewables support mechanisms. Both of those targets are on top of the European Union energy policy agenda, but little effort is made to incorporate their mutual dependencies into actual regulation. For some, decarbonisation should be achieved solely through cap-and-trade system named EU ETS, where renewable generation technologies should only be chosen by the market when they are assessed individually profitable under increasing EUA prices. This would make subsidies for RES superfluous, and indeed inefficient. Others point to past failures of EU ETS system and vigorously argue that decarbonisation should be driven mainly by expanding renewables in the power systems. To compare those conflicting views, I construct capacity expansion plan that assumes increasing, together with intensifying global warming, social costs of carbon passed-through to carbon emitting installations, and then compare the outcomes with the high RES scenario.

Lastly, critics of decarbonisation often argue that decarbonising power sector, either through supporting carbon neutral generation or penalising CO_2 emissions, may or may not be technically feasible, but would otherwise lead to prohibitively high power system costs. To verify this thesis, I develop business-as-usual scenario that assumes no CO_2-driven environmental measures in the power sector. This baseline capacity expansion plan is used to assess incremental cost growth, disregarding environmental effects, when either of the two decarbonisation mechanisms are employed to combat global warming.

2 Research method

The dissertation makes use of mathematical optimisation as main research method to reach the above-stated objectives. In particular, it draws from extensive literature on security-constrained economic dispatch and capacity expansion planning in the power systems, joining both problem types in a modified stochastic dual dynamic programming algorithm framework. Building on theoretical background of competitive electricity auctions solutions, model presents three distinctive power system visions till 2030.

Fundamental models of power systems are versatile tools used widely across different functions within power industry, from utilities all the way to market regulators. The models are usually fit to purpose and therefore their capabilities may encompass market design, investment planning, decision support in everyday trading and portfolio optimisation activities of utilities or even financial planning. The model developed in the dissertation combines two seemingly disjoint fields: capacity expansion planning in long time horizon and hourly operational dispatch decisions. This allows the model to precisely capture the actual benefits of keeping different capacity types in markets increasingly influenced by intermittent energy sources. Furthermore, with the use of SDDP, the recursive nature of those two time frames can be solved in relatively few algorithm iterations.

Among others, two major industry-wide developments can have a profound impact on the future development of power markets: awakening of demand side response and technological breakthrough in cost-efficient battery energy storage. The model can readily cover the former and the latter, assessing both market potential and the impact they may have on future energy mix. Model's versatility is both theoretically and practically useful, but does not come without a cost, in particular requiring much attention to be given to efficient numerical implementation.

The challenges of the model's implementation are overcome using analytical results on modelling power markets competition and economic dispatch, as well as by exploiting model structure with a limited number of complicating variables by using Benders' decomposition. Using efficient decomposition methods holds several major advantages, both theoretical and practical. On the practical side, the curse of dimensionality, frequently plaguing long-term forecasts, can be dealt with by using Benders' cuts and restricting state space on the backward passes of the SDDP algorithm, also contributing to much reduced use of memory and decreased model solve runtime. Decomposition also contributes to more realistic decision making, especially forward looking nature of investment decisions, and allows the modeller to better structure the impact of weather uncertainty on renewable generation and electricity demand.

The changes introduced to the original SDDP algorithm, in particular replacing feasibility cuts with analytical solution, are covered in detail in a separate chapter. The description also covers the technical aspects of model's implementation in programming environment, allowing for a step-by-step analysis of the model in General Algebraic Modelling System (GAMS).

3 Study results

Three distinctive power system visions are developed and acutely presented in the dissertation. Those visions differ in how they approach the regulation of decarbonisation, but otherwise share identical input parameters. The comparative analysis is then carried out. By showing differences in projected market outcomes under optimal solutions, the following conclusions are drawn from the study.

1. The Pigouvian decarbonisation mechanism, presented in the study, can be efficient in decarbonising the power system in Poland. When correctly done, it can lead to market-based, i.e. devoid of subsidies, development of renewable energy sources as well.
2. The centralised power system dominated by RES is a technically feasible prospect. This holds true even with an extreme 80% share of renewables in the power mix, under several provisional assumptions, including facilitating the use of power systems interconnections.
3. The interdependency of RES support schemes and decarbonisation mechanisms can only be described as deeply fundamental, up to the point of being interchangeable. The results provide convincing evidence of current EU ETS cap-and-trade design delivering flawed outcome, with little anticipated chance of getting significantly better in the future. The conflict between EU ETS and RES support schemes will continue to, most likely, derail

market-based decarbonisation efforts, unless thorough design review gets underway.

4. While the CO_2 taxation and RES paths differ in many ways, whichever decarbonisation path is chosen in the end, the total electricity bill for the customer in Poland is projected to sharply increase. This result is clear, even under relatively optimistic assumptions for natural decommissioning of existing generation assets and impressive technological progress for RES, with RES-bound scenario delivering roughly 30% jump in the electricity bill.

Separate chapter is devoted to thorough review of results for RES scenario, in particular technical feasibility, by looking at system balance stress events. Multiple, scenario-enabling preconditions are found. While none of which seems particularly stringent, they still point at several important implications for the power systems of the future. Two in particular stand out: the role of power system interconnections and seemingly imminent review of current transferable utility mechanism, i.e. short term electricity market pricing.

With regards to the former, RES expansion can be made more cost efficient with the use of interconnections. Although indirectly, that's also saying that, at least in part, rapid development of RES in any country can come at indirect cost to neighbouring markets, potentially abusing their role as balancing entities. Concurrent RES development in several closely-linked markets, due to significant correlation of photovoltaic generation, may diminish the perceived benefits of making markets more interconnected. In either case, there needs to be control over power output of non-dispatchable RES in order to achieve the optimal costs of running the system with high RES outputs.

The latter condition shows a space or, possibly, a need to revisit current remuneration mechanisms on the power markets. With more and more high CAPEX/zero-marginal cost intermittent generation coming online, there's bound to be friction over current short-term, common-value, uniform first-price auction mechanism delivering main remuneration stream for generation assets. In particular, the feasible and optimal capacity mix of 80%-renewables share scenario for Poland in 2030 retains 27.9 GW of conventional and 6.8 GW of storage assets. Of these, large part is mostly backup, in the extreme cases used only once every three years. This result may seem contradictory at first, after all significant RES subsidies would be required to achieve a power system transformation of this magnitude in the first place. Providing, at the same time, additional remuneration outside of short-term revenues to conventional generation looks counterproductive. The model's goal function formulation is, however, equivalent to welfare maximisation and therefore puts significant value in securely delivering uninterrupted electricity schedules to customers. The optimal way to achieve this goal leaves much room for conventional resources too.

The model developed in the dissertation combines two seemingly separate modelling worlds: precise reconstruction of hourly generation schedules and prices and long-term investment and disinvestment planning horizon. It does so with the aim of correctly capturing the costs and benefits of different generation and storage technologies, while providing technically feasible capacity mix that can securely satisfy load, even at extreme weather events. More common approaches focus either on short-term market outcomes, lacking in investment optimisation component or merely using a rolling horizon to heuristically add and subtract capacities, or go solely in the long-term direction, disregarding short-term nature power system balancing. The tools using the latter are still the mainstream, despite all the evidence pointing to weather uncertainty making their original design largely obsolete.

4 Dissertation outline

The first chapter provides introduction to the power market in Poland and, briefly, other competitive markets. The economics of the market are described with reference to general concepts, such as auction and mechanism design, game-theoretic competition modelling and the research field of externalities. Given the hypotheses of the work, particular attention has been given to European Union Emissions Trading Scheme and social cost of carbon, concept that has been put forward by environmental economics. The chapter concludes with listing and describing current mechanisms for utility transfers in the power sector in Poland.

The second chapter builds on two major optimisation problems in the power sector: security-constrained economic dispatch and capacity expansion. Starting with the basic versions of the two, optimisation techniques are successively build up to incorporate uncertainty, dynamic decision making and problem decomposition. Whenever new elements are introduced, minimum working example is provided to familiarize oneself with how it may affect the optimisation outcome. The structure of this chapter allows a seamless transition from the original specifications of capacity expansion and economic dispatch problems to the final model structure presented in the following chapter.

The third chapter provides formal mathematical definition of the model, that is later used to validate the hypotheses of the dissertation. It builds up on the previous two chapters by weaving together economic and technical concepts of the Polish power sector with the formal, stochastic and dynamic mathematical optimisation problem framework. Each and every element of the model is thoroughly described, where alternative formulations of constraints or elements thereof were possible, justification is provided as to why a particular design prevailed. The chapter later follows with a description of the process of developing real world problem into an optimisation problem. This includes, but is not limited to, description of the programming techniques employed to ensure bug-free model implementation and satisfactory runtime.

The last chapter presents a case study of the power system development in Poland until year 2030. The case study, preceded by the assessment of model performance, consists of three separate visions of the future of the power sector in Poland. Those visions are later used to draw conclusions on the hypotheses of the dissertation.

5 Future work

The process of developing an optimisation model always balances model tractability and accuracy. While, on one hand, one would like to have the model resemble the reality as closely as possible, it quickly becomes apparent that this leads to increasingly complex and likely incomprehensible model implementations. However, each time a compromise on modelling dimensionality or precision is introduced, one should take note of the trade-off that has been made. Alas, this has also been the case in this work and several areas worth exploring are still available for pursuit. One particularly apparent, although requiring the dissertation to take an altogether different direction and therefore abandoned, is the likely pressure on the markets to remunerate availability, rather than almost solely production, of the generation and storage assets. If true, this conclusion will likely lead to an overhaul of many of the flawed current market mechanisms in the power markets and result in an opportunity to redesign the markets using state-of-art knowledge on mechanism design.

Among other potential research areas, fully listed in the conclusions of the dissertation, are the following.

1. Changing model pricing from zonal to nodal. While it is not the direction that EU is pursuing now, it is still a well represented design in the U.S. and, at the same time, the most cost-efficient way of running the short-term power markets. If implemented, this extension would allow, in addition to current features of the model, to capture the asset localisation in the optimisation problem and, at least potentially, substitute investment in generation with transmission.
2. Replacing the investment decision criteria. The current modelling choice was to go ahead with expected value of discounted return from investment, but multiple other choices are readily available and could be developed to acutely reflect the actual risk preferences of the investors.

3. Replacing the short-term bidding strategies of the market players. If the objective of the model was to assess competitiveness of the power sector and changes thereof, further work on modelling competition would be advisable.
4. Optimising over scenario trees. Together with further work on investment decision criteria, this direction would take the model to a state allowing the modeller to assess the costs of regulatory uncertainty and mechanisms altering investors' risk profile. This extension could make use of current, up-to-date research on scenario generation and reduction techniques.
5. Expanding the spatial dimension of the model to several areas/countries. While this approach would retain current NTC approach to external borders of the modelled region, it could co-optimise the investments in generation and interconnections in multiple areas at the same time. This direction would be useful in, *inter alia*, allowing the modeller to provide cost-benefit analyses to publicly funded investments in interconnections.
6. Detailing the model with regards to decentralisation of the power sector. Taking note of the current tax-focused cost structure of the electricity bill, it seems more and more likely that part of the market may be shifting to self-supply. Modelling those decisions would provide a better understanding of how commonly introduced support measures, such as *net metering*, are affecting the total system costs.

The above-mentioned extensions to the model, while introducing an additional layer of complexity, provide the modeller with means to address new and challenging problems faced by the power sector.