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CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

HydroCen brief Nr. 15

Pre-project: Fundamental modelling of a 100 % renewable electricity system

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STED/DATO	Trondheim, 20.03.2022
SAMARBEIDSPARTNERE	
PROSJEKT I HYDROCEN	Open Calls

NTNU SINTEF NINA

English version:

Content

Abstract

The memo summarizes the literature review that was carried out as part of the development of the KSP application "RES – Modelling a 100% Renewable Electricity System".

Introduction

A 100 % renewable electricity system is probably needed for EU to reach is goal to be climate neutral by 2050. Such an electricity system will consist of known production technologies as wind and solar power, bio and hydro, but must also include much more end-user flexibility. Increased storage capacity from, e.g. batteries and power-to-X, is also needed. The coupling to other sectors will increase since a fully renewable energy system must facilitate a higher degree of electrification.

The goal of this pre-project was to build knowledge on the scientific state-of-the-art on market modelling representing a 100 % renewable electricity system. The knowledge building supported the application of a main KSP-project on the same topic submitted to the Research Council of Norway in February 2022.

In the following we present the reviewed literature. We underline that this memo is not a complete and comprehensive review but can be read as a collection of recent and (in our view) interesting modelling efforts, analyses, and views on the topic.

Review

Analyses made by Norwegian stakeholders

In 2021 Statkraft presented a global low-emission scenario towards the year 2050[1]. The important roles of solar and wind power, north-sea offshore grid, hydrogen, etc. are discussed. It is stressed that, development trends that were considered "optimistic" has now changed to "conventional" in a short time. The scenarios were constructed taking a forward-looking approach, following politics, technology trends and costs, as well as market dynamics. This is different from the many "backward looking" approaches that we reviewed using expansion planning models aiming at a pre-defined target development.

In 2021 the Norwegian regulator (NVE) presented a power market analyses towards 2040[2], providing scenarios for system expansion and analyses including power prices for those. Three models were applied: TIMES for defining the demand, and TheMA and Samnett for detailed power system simulations. The projections changed considerably since the last analyses in 2020. One of the factors driving this change is the updated EU policy on targets for emission reduction, constraining the CO2 quota market, which in turn impacts power prices and favours the profitability of power from renewable sources. The report discusses sector couplings affected by changes in CO2-pricing; Only first-order effects (such as higher marginal cost on thermal) are seen in a traditional system simulation, while second-order effects (such as higher demand for electricity due to more EV) are not captured. A significant amount of electricity consumption for hydrogen production in 2040 is assumed (7 TWh), but it is also pointed out that other technologies may outperform hydrogen as the flexible consumer of surplus power.

General

A comprehensive list and classification of research on 100% renewable energy systems is prepared in (Hansen, Breyer, & Lund, 2019). In the period 2008-2018, the number of publications on the topic has grown from practically zero to more 40 per year in the two latest years. It is argued that research points to the need of a cross-sectoral holistic approach, combining the sectors of electricity, transportation, heating and cooling. The authors concludes that existing literature mostly focus on the electricity system and the supply side. The majority of the references presented in the following are newer than those covered in the review of (Hansen, Breyer, & Lund, 2019).

(Oei, Burandt, Hainsch, K., & Kemfert, 2020) provide an introduction to the recent scientific discussions on the feasibility of a fully renewable system. The importance of the energy trilemma is pointed out; the future power system should be feasible along the axes of reliability, security and affordability. Experiences and challenges with the global expansion planning model GENeSYS-MOD are reported.

(Joskow, 2019) explains the US wholesale market design and its flaws when facing large-scale integration of RES. Scarcity pricing and marginal (short-run) opportunity cost of demand are central topics. The adaption of energy plus capacity markets recognizing that energy-only markets with price caps do not yield sufficient revenues to sustain existing capacity and to attract new generating capacity. What happens at the tails of price duration curve will become more important. The author shows by example that flexibility (storage and demand-side response) is needed in a 100% renewable system in equilibrium. The spread of smart meters will improve scarcity pricing possibilities. The author expects that competitive retail suppliers will begin to offer demand management products in response to variable pricing that trade the right to partially control the customer’s consumption during high price hours for a more stable and partially hedged retail price structure provided to these customers. The author sketches a market

[1] https://www.statkraft.no/globalassets/0/.no/nyheter/lavutslippsscenario/Statkraft-lavutslippsscenario-2021.pdf
[2] https://www.nve.no/energi/analyser-og-statistikk/langsiktig-kraftmarkedsanalyse/

design with high (but not 100%) RES and with centrally controlled auctions to attract necessary storage and dispatchable resources.

Expansion planning models

Using the SCOPE Scenario Development (SD) framework (Böttger & Härtel, 2021) analyses the effect of cross-sectoral demand bidding for the price formation in future, carbon-neutral electricity markets. The authors discuss new plateaus in the market price duration curve, especially at low marginal cost of production, and present price-duration curves where the impact of each technology is presented. With all new technologies considered, only few low-price periods are left. A related study is documented in (Härtel & Ghosh, 2020).

The Low-carbon Expansion Optimization (LEGO) model (Wogrin, Tejada-Arango, Bachhiesla, & Hobbs, 2021), is an open-source model based on mixed integer quadratically constrained optimization (MIQCP). It comprises modules e.g. for expansion planning, economic dispatch, unit commitment, frequency control, battery degradation and demand response. Flexibility in the discretization of time allows the treatment of shorter-term problems in the expansion planning. Demand-response is modelled as a response to a predefined price and by load shifting. A fixed demand for hydrogen is assumed and electrolyzers are built to serve this demand. Further plans for integrating with a hydrogen network and the hydrogen demand side are discussed. A comparison with a set of existing expansion planning models is performed. Hydropower is not explicitly mentioned.

The EMPIRE expansion planning model (Backe, Skar, del Granado, & O. Turgut, 2022) represents uncertainties and decisions in a multi-horizon scenario tree, where long-term (strategic) and short-term (operational) are treated. The underlying assumption is that the strategic uncertainty must be independent of the operational uncertainty, and that the strategic decisions must not depend on any particular operational decisions. The last assumption is a strong one for hydro-dominated systems. Operational decisions are made for a shorter sequence of time in a given season.

Recent work targets a 100% renewable system by use of a fundamental market model that allows for expansion the hydropower-dominated system of New Zealand[3]. The main emphasis is on supply adequacy when reservoir inflows, wind, and solar energy are uncertain or variable. The alternative of constraining CO2 emissions lead to a different and better expansion plan. The presented model has similarities to the EMPIRE model but allows a more detailed hydropower representation.

Simulation models

(Gholami, Poletti, & Staffell, 2021) uses a cost-based dispatch model to simulate market prices, analyzing if energy prices support cost recovery for the New Zealand system. Hydropower accounts for 40-50% of energy generation in the considered scenarios. Discusses merit order effects in the near and long-term when transiting to a fully renewable system. Combine scenarios and generation expansion model (GEM) to define the system in 2035, ensuring that the ratio between installed capacity and peak demand is the same as in the current system. Demand response through curtailment and no batteries. The authors find that the new system leads to seasonal imbalances, and prices below LRMC, pointing to the need for redesigned markets.

[3] http://www.epoc.org.nz/papers/100PercentOperResv10.pdf

Demand-side flexibility

The flexibility on the demand side is expected to increase with the ongoing entrance of Advanced Metering Infrastructure (AMI) (Shariatzadeh, Mandal, & Srivastava, 2015). The use of AMI can make it both possible and attractive for consumers to react to short-term variations in power prices, and it also provides a basic infrastructure for automatic load control. Furthermore, the volume, type and variability of demand is expected to change, due to plans for further electrification of the energy consumption in transportation, offshore installations, and industry sectors. Thus, the rather inflexible consumption patterns seen in the past, with a marginal value for most of the demand equal to value of lost load (VoLL), are likely to change significantly. A relevant review on the modelling of demand-response in power market models is provided in (Morales-España, Martínez-Gordón, & J. Sijm, 2021).

Discussion

The literature review reveals a significant effort in many countries and systems for modelling and analysing a possible future 100 % renewable electricity system. The task is certainly challenging; one needs to anticipate the development of the fully renewable system (which technologies and how much) and be able to model it in detail. Additionally, the presence of hydropower (as a renewable generation technology) puts further requirements to the modelling due to its long-term storage capability.

As guidelines for the modelling, many authors stress that the new insight generated by such models is more important than the actual numbers themselves. Moreover, the importance of scenario feasibility, in terms of reliability, security and affordability, is important.

Many authors points to a more active demand-side as the key for facilitating a 100% renewable system. In particular, what happens at the tails of price duration curve will become more important. Possible takes on an active demand-side:

- The demand curve should adapt to ensure reasonable prices and cost recovery for producers. What are the types and quantities of demand-side technologies that provides this equilibrium?
- There needs to be enough flexible consumption of long-term "surplus power". This argument often leads to the defined need for hydrogen, or more generally to power-to-X. It will be important to mathematically describe such processes, including demand, saturation effects, possible correlations to exogenous power system parameters, etc.
- Some authors argue that a fully renewable electricity system will challenge the current market design. Will the markets provide reasonable price signals in constrained situations?

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