Open-source electricity market modelling for the Baltic states: review and requirements

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Abstract—**This study strives to develop an open-source model for studying the Baltic electricity market. An important step towards this goal is assessment of the existing modelling landscape. Therefore, in this paper we present an overview of the modelling approaches and a non-exhaustive review of existing open-source energy modelling tools, listing also frameworks that have been applied for studying the Baltic energy system. Based on the review and needs analysis, we devise the main requirements for the further development efforts of the Baltic electricity market model.**

***Index Terms*-- electricity markets, modelling, optimisation, open source, energy transition**

I. Introduction

Lately, electricity markets have been experiencing notable developments. While market liberalisation introduced a novel paradigm, the energy transition and recent price crisis continues posing unexpected challenges, sometimes questioning the viability of existing markets. Significant changes might be needed to keep accommodating increasing shares of zero-marginal-cost renewables while also providing clear investment signals. Hence, detailed analysis and in-depth modelling of market frameworks is required to assess the effect of the potential changes on the market outcomes and its various actors. To that end, the paper provides an overview of the existing open-source energy and power system models that can be adapted and employed to analysing power system operation under various market frameworks and future scenarios. Based on a non-exhaustive review of the available models and needs analysis, the requirements for an open-source market modelling tool under development aimed at analysing the Baltic region are devised. It should enable studying both the existing wholesale markets as well as new ancillary services to be introduced in the Baltic states by 2025 when synchronisation with Continental Europe is due. While the ultimate aim of the study is to develop a multi-functional open-source modelling tool for electricity market research applicable to a multitude of use cases, this paper serves as a starting point and outlines the first steps towards this goal.

We start with an overview of energy system modelling approaches before moving on to existing open-source models that can be employed for analysing energy system development paths, optimising its operation under various future scenarios as well as for market simulations. Furthermore, a few open-source modelling examples covering the Baltic energy system are presented. Finally, based on the modelling tool review and the needs identified, we devise requirements for the further development of an open-source Baltic electricity market model.

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II. Energy System Modelling Approaches

Energy system models can be overall classified as top-down or bottom-up depending on their analytical approach. Top-down modelling focuses on studying the energy system on macro-economic level with a simplified representation to consider long-term changes [1]. Instead, the focus of our study is the most widely used bottom-up energy system modelling approach [2] with a high degree of techno-economic detail [3].

Next, depending on the model paradigm, we can distinguish between four main groups, namely, energy system optimisation models, energy system simulation models, electricity market and power system models and qualitative and mixed-methods scenarios [4]. Widely used examples of large established bottom-up optimisation model families are MARKAL/TIMES and MESSAGE which aim "to represent possible evolutions of the energy system on a national, regional or global basis over several decades" by minimising total energy system cost. Another group, power system and electricity market models, deals specifically with electricity. Power system models have been traditionally used by utilities for decision support starting from investment planning to operational strategies, whereas market models focus on physical properties (e.g. balancing) and concern liberalised markets. To that end, WASP and PLEXOS are among the most commonly used commercial large-scale power system models. With the increasing role of variable renewable energy (VRE) sources e.g. in determining prices, models aimed towards electricity market have evolved and moved into the domain of large energy system models [4]. Moreover, due to the increasing role of electricity as a clean energy carrier, power and energy system models have been gradually converging [5].

Lately, the energy transition has brought about new challenges due to the variability and uncertainty of VRE sources in contrast to conventional baseload or dispatchable generation. This requires a high temporal resolution which can unlikely be fully addressed by the traditional optimisation models such as MARKAL, MESSAGE or TIMES. When modelling renewables, the data should be sufficiently resolved also in space, considering real weather as well as its correlation between sites [4]. Several studies have demonstrated that a low temporal resolution can lead to overestimated penetration of VRE sources and thus an underestimation of the necessary investment. Hence the need to better address the challenges of VRE integration has been a major driver for the high level of activities around model development seen recently, with many new models and modelling features appearing in the literature [2].

As concerns market models, another challenge is dealing with imperfectly competitive markets, which are much more complex to represent. This can be especially true in small regions such as the Baltic states with few power producers with large market shares. Thus, imperfect competition requires maximising the profit of each participant simultaneously. Overall, [6] identifies three major trends in electricity market modelling: optimisation, equilibrium and simulation models. The first group deals with single-firm optimisation typically used for unit commitment (UC), short-term hydrothermal coordination or strategic bidding. Instead, equilibrium models consider competition among all participants and represent the overall market behaviour within a traditional mathematical programming framework [6]. More complex problems can be addressed by simulation models. They often use bottom-up approach with a high level of technological details to allow testing of various system topologies and developments of different scenarios [2]. For example, system dynamics is a multi-disciplinary modelling approach for examining non-linear problems subject to feedback loops [7]. Agent-based simulation, stemming from the game-theory concept of equilibrium, is a specific case of models representing each agent's strategic decision dynamics by a set of sequential rules that can range from scheduling generation to constructing market offers and include a reaction to their competitors prior behaviour [6]. While simulation and imperfect market equilibrium models are employed for market power or market design analysis, equilibrium models have been also used for long-term hydrothermal coordination or capacity expansion planning. The dynamics of agent behaviour can be best replicated by adaptive agent-based simulation techniques [6]. While game theory supposes perfect information and rationality, agent-based approach allows graduating the information available to the participants and their rationality. However, agent-based models "take more time to be solved and results may be difficult to interpret" [8].

III. Overview of Open-Source Modelling Tools

A. Optimisation Tools

Nowadays, there is a steady trend towards openness and transparency in energy modelling. Open code and data improve scientific quality through increased transparency and reproducibility, fostering effective collaboration [5]. One can find both recent open-source development efforts as well as already established, previously proprietary, energy modelling tools being released as open-source. Balmorel (the Baltic Model of Regional Electricity Liberalisation), released in 2001 and written in GAMS, was the first open energy system model framework [5]. It is a partial equilibrium model for simultaneous optimisation of generation, transmission and consumption of electricity and heat under the assumption of perfectly competitive markets [9]. The objective is to maximise social welfare subject to technical, physical and regulatory constraints with linear optimisation (mixed-integer modelling may be applied e.g. for UC). Being a long-term bottom-up energy system model, it has high and flexible temporal, sector-coupling and geographical resolution [9], [10]. However, power system reserve management is out of model scope. Furthermore, energy producers act as price takers in the market without any strategic behaviour. Thus, Balmorel is less suited for markets with clearing conditions significantly differing from those under perfect competition [9].

During the last decade, a number of open-source energy system models and modelling frameworks have been published such as Backbone, Calliope, OSeMOSYS, PyPSA, oemof and SpineOpt among others [11]. Calliope is an energy system modelling framework written Python, designed to analyse systems with arbitrarily high spatial and temporal resolution and a scale-agnostic mathematical formulation. Having the ability to execute many runs based on the same base model, its primary focus is on planning energy systems at scales ranging from urban districts to entire continents employing linear programming (LP) [12]. Unlike traditional power system modelling tools, it does not provide e.g. power flow analysis [13]. Euro-Calliope is a European energy system model implemented within this framework with hourly resolution (including data for multiple weather years) and a three-level variable spatial resolution up to sub-country regions [14].

Many other open-source modelling frameworks/tools such as PyPSA, oemof, Spine Toolbox and OSeMOSYS to name a few are also written in Python [15]. (The latter is also available in GNU MathProg and GAMS.) The Open Source Energy Modelling System (OSeMOSYS) is a deterministic LP tool for modelling of long-term energy investment pathways (optional MILP possible for generation capacity expansions) [17]. Having a compact, easily accessible code, it has been widely used for education, capacity building and stakeholder engagement [18]. While its "block modelling approach" significantly simplifies development of long-term energy models, it has certain limitations as concerns the modelling of low-resolution operational problems. Moreover, its core structure with lacking intertemporal constraints precludes adequate assessment of flexibility issues [19].

PyPSA toolbox (Python for Power System Analysis) can simulate and optimise electric power systems coupled with related energy sectors. Compared to the above-mentioned frameworks, it combines traditional steady-state power flow analysis with energy system modelling, thus enabling multi-period optimisation of operations and investment [20]. Similarly to OSeMOSYS, it has a wide user community worldwide with additional extensions and regional models developed. For example, PyPSA-Eur is the first open model dataset of the whole European power system at the transmission network level [21]. Based on that, PyPSA-Eur-Sec is being developed by adding a number of energy demand/supply sectors (transport, heating etc.) [22].

The Open Energy Modelling Framework (oemof) can be used for optimising multi-sectoral energy systems at different scales employing mixed integer linear programming (MILP). oemof provides a toolbox for constructing comprehensive energy system models based on a generic graph-based description suitable for cross-sectoral modelling with various approaches. It encompasses "model generator methods" for generating economic dispatch, investment and UC models and allows quick switching e.g. between dispatch and investment modes. Existing oemof applications include electricity market models, detailed UC for district heating among others. Compared to other open-source tools such as Calliope, PyPSA, and OSeMOSYS, it distinguishes itself with a highly collaborative development process to facilitate "a maximum level of participation, transparency and open science principles" [16]. oemof has been also highlighted as having the highest number of GitHub commits and branches by [15]. With the strict open-source, non-proprietary philosophy, it claims to be particularly suitable for new developers and users. Its flexibility allows for adjusting the model along with evolving research objectives e.g. in project-based research [16].

SpineOpt is an energy system modelling framework written in Julia for planning and scheduling energy and power systems via MILP allowing for high customisation of the energy system due to its highly flexible temporal and stochastic structure. Compared to other open-source models, SpineOpt combines a diverse range of modelling features with a high level of adaptability and enables having different temporal resolutions and stochastic structures for various parts of the same model [19]. Moreover, it supports rolling horizon optimisation on a dispatch level, which is missing not only in OSeMOSYS and PyPSA [19] but also in 29 other open source models reviewed in [15].

The SpineOpt model is primarily intended to be run via Spine Toolbox, open-source software written in Python for defining, managing, simulating and optimising energy system models which allows managing input data, scenarios and workflows as well as archiving and visualising the results [23]. Designed to support execution of multi-energy integration models, Spine Toolbox also facilitates convenient model linking through its user interface. Since this functionality is model-agnostic, it can be used for orchestrating complex energy system modelling workflows [19]. A few additional strengths of Spine Toolbox compared to other open-source modelling frameworks are e.g. integration with external API (not supported by OSeMOSYS and Calliope) or extendable modelling framework and multi-language support (missing in PyPSA) [23].

B. *Agent-Based Modelling*

Most fundamental optimisation models typically employed for determining cost-optimal system operation and configuration are built on the assumption of perfect competition. They implicitly assume that the decisions of market participants are based on financial criteria from a centralised perspective and "under full transparency of information", therefore the resulting cost-effective solution supposes these ideal conditions. Such optimisation models are employed for analysing long-term policy effects, investigating power system operation and evolution and examining complementary flexibility sources in power systems with high penetration of VRE sources. Consequently, they can provide e.g. the minimum cost for reaching specific energy policy targets [24].

However, when devising political and regulatory frameworks to facilitate meeting the set objectives, it is imperative to consider the real behaviour of the actors. Capturing their individual decision-making behaviour is enabled with agent-based models (ABM), which can analyse market effects and market design aspects resulting from various uncertainties and distortions e.g. imperfect information, market power, bidding strategies, support schemes etc. [24]. Nevertheless, when reviewing the scientific literature and the published open-source models for energy systems, it is evident that the number of readily available agent-based simulation models is much smaller compared to energy and power system optimisation models [25].

AMIRIS is an agent-based market model for the investigation of renewable and integrated energy systems and has been open-sourced in 2022 after more than 10 years of development. Developed as a Java application to be configured via Python scripts, it computes electricity price endogenously by simulating strategic bidding behaviour of prototyped market actors, which does not only reflect their marginal cost, but can also consider policy effects, e.g. support instruments, market power etc. Though the available examples of model implementation include only Germany and Austria, AMIRIS can simulate even large-scale agent systems in a short time. Moreover, no prior skills are strictly necessary to configure and run the model [26].

Agent-based Electricity Markets Service (EMS) is a publicly available open access web service for simulating electricity markets, although not open-source. The service is based on the market operator agent simulation from the broader Multi-Agent Simulator for Electricity Markets (MASCEM) to perform market clearing based on the market player strategies (bids). EMS is available as a REST API and has been demonstrated e.g. in conjunction with the Spine Toolbox for simulating three main European electricity markets and auction-based pool mechanisms [27]. While EMS supports both day-ahead and intraday markets with complex conditions for simulating MIBEL (Iberia), only the day-ahead market is implemented for EPEX and Nord Pool simulations. There are hourly and block orders for Nord Pool and EPEX albeit without complex constraints. Additionally, Nord Pool simulation includes flexible hourly orders.

C. *Open-Source Modelling of the Baltic Energy System*

While there are have been a number of modelling studies using various methods to optimise Baltic energy system future scenarios, this region is still less comprehensively covered compared to Nordic and Central Europe [28]. Moreover, only a few studies focussing on the Baltic states have developed or utilised open-source models/tools. A recent example is the open-source Baltic Backbone model, written in GAMS, which covers power, heat, building and transport sectors of Estonia, Latvia, Lithuania and has been employed in [28] to study the operational impacts of energy transition and desynchronisation on the Baltic energy system from 2017 to 2030. To address the need to model the impacts of high VRE shares with high temporal resolution and multiple sources of flexibility, they optimize the hourly operation of Baltic energy system and analyse various operational, environmental, economic, and security indicators. Optimisation is performed by minimising overall annual system costs. Investments are out of scope of the optimisation and are instead calculated outside the model (for the power and heat sector) or not considered (for transport and buildings). The Baltic Backbone has been validated against the statistics of 2017 and, while the generation output is very similar to the historical data, there are larger discrepancies as concerns the cross-border electricity flows due to the limited regional scope and the resulting simplified electricity trade and reserve modelling in the neighbouring countries.

Another example of a GAMS-based open-source model used for modelling of the Baltic states is Balmorel which is usually employed for long-term analysis. E.g. it has been used in [29] for analysing the impact of potential future climate policies until 2050 and assessing measures required in the Baltic countries to reach the energy and climate targets set by the EU. Within this study Balmorel simulations have been performed for a large geographical area covering the Baltic and Nordic countries along with the rest of Europe except for the Iberian Peninsula and Balkan countries. Furthermore, Balmorel, which provides detailed analysis of electricity at country level and district heating at sub-national level (for Baltic states), has been linked with TIMES-VTT, which gives overall projections of energy demand, supply etc. and models the Nordic and Baltic countries as a single region, and the remaining EU as another region. Among the three Baltic countries, Balmorel has been a popular model for electricity and district heating sector analysis especially in Estonia [9], [29]. However, its usage by a wider community is constrained by the commercial GAMS language as is the case also for the Backbone model.

The Baltic states power system on a country-level has been also included within ODIN, an open dispatch model for the Nordic power system [30]. It has been developed in Python and includes all data required for annual simulations. ODIN developers admit that even though there are several models covering the Nordic power system, only Balmorel and Calliope have sub-national spatial resolution for the Nordic countries. Still, this resolution does not correspond to the actual price areas and the models "have not been validated to reproduce historical production patterns" [30]. ODIN aims to fill this gap by modelling the Nordic countries at sub-national level to simulate internal congestions and has been validated against historical production and transfer patterns. It is claimed to be the only open-source model representing all price areas of the Nord Pool market [31]. Unlike many other models, ODIN employs a quadratic objective function resulting in smoother production profiles and eliminating the need for cycling costs to limit excessive ramping of units. In addition to modelling the Nordic countries at regional level, the model geography includes Estonia, Latvia, Lithuania, Poland, Germany, the Netherlands and Great Britain, and validation on 2019 data for each of those countries has been reported in [30]. The open-source model, which has resulted from a PhD thesis [31], is at an early stage and, for the time being, lacks comprehensive documentation [30], [32], hence potentially hindering its usage by a wider community. It has been used for a few use cases, e.g. to study curtailment in the Nordic power system in future scenarios with increased VRE production [31].

IV. Requirements for the Baltic Model

The open-source model review allows us to formulate a list of requirements an electricity market model has to adhere to focussing especially on the Baltic context considering the regional challenges resulting from the energy transition and synchronisation with Continental Europe. In addition, a number of requirements arise from assessing the needs of the prospective users and the respective modelling use cases.

A. Technical Requirements

We begin with general requirements that deal with the model development/maintenance process and user experience. First, considering an ambition for the model to be (reasonably) widely used also outside the academic community, it should be usable with minimum technical hurdles. It is preferable to strive towards limiting the number of interpreters, frameworks and additional tools that need to be installed and/or configured and to automate the setup process. Since not always this is an attainable goal, at the very least the setup documentation needs to be very exhaustive and anticipate the typical issues that might arise. Nevertheless, from the user perspective, it is beneficial if the model components can, at least, be limited to one programming language. Since, in our review, we have observed a growing trend within the modelling community to write or even convert their models into Python, or to, at least, develop interfaces that can be accessed via Python, it is identified as the most promising programming language for developing an open-source model. It also has the major advantage of not requiring the user to secure funds for acquiring licences as is the case for, e.g. GAMS or MATLAB.

The second requirement from the model development point of view is to not "reinvent the wheel". In other words, the power and energy system modelling landscape is already evidently proliferated with a large number of models and modelling frameworks, often enough with overlap in functionalities. Because of this, the reasonable course of action is to incorporate and use the already existing open-source tools as much as possible (subject to their license terms) and only add new components to the extent that is necessary to fill a present gap. At first glance, this requirement might seem to be at odds with the first one, since it naturally leads to an aggregation of tools. However, these requirements ultimately go hand in hand. For instance, Spine Toolbox has proven to be an excellent tool to manage a modelling workflow where several models and modelling support tools can be interlinked into one seamless process [33].

Specifically in our case, as was shown in the previous sections, there are already some models that deal with the Baltic power system in the context of decarbonisation pathways and operation with high shares of VRE. However, the issue is not studied in-depth from the electricity market perspective, which has emerged as a topical need in the region. While there are some large-scale models dealing with electricity market issues that include (or have the apparent capability to include) also the Baltic states, the localised nature of the topics to be studied drives us towards developing a model tailor-made for the Baltic electricity market. Such an approach has the additional benefit of making it less computationally expensive (and thus providing room to expand the technical detail), limiting the amount of data that needs to be collected and maintained, while allowing to localise and isolate the market issues studied. Moreover, large pan-European models can have more pronounced data quality issues with a larger impact on smaller countries.

To ensure continuous usage of the model, it is indeed important for input data to be as freely available as possible and up-to-date. We can identify at least two major groups of input data. The first one is timeseries of variables such as demand, inflow, wind speed, solar irradiation (for different weather years) etc. These timeseries serve both for devising the demand and production patterns and also for validating the model on known historical data. The other group concerns assumptions on the future energy system, e.g. installed capacities, annual consumption, interconnector developments etc. In terms of timeseries, a lot of valuable data is available from the ENTSO-E Transparency Platform. Unfortunately, a large part of it cannot be freely redistributed without the permission from the multiple owners of the data [30]. However, this can be addressed by incorporating in the workflow a data crawler to collect the necessary data when required, e.g. as in [30]. For future assumptions, it is paramount for the Baltic electricity market model to be properly aligned with the plans and forecasts of major local stakeholders, e.g. concerning the LV–SE4 interconnection, large-scale storage projects, expected decommissioning of existing and commissioning of new power plants, interconnection reconstructions etc. The most important source for this are the three Baltic transmission system operators (TSOs) who annually publish their ten-year development plan. At the very least, the model to be developed needs to be linked with a curated and regularly updated database, reflecting the changes in local stakeholder projections. The TSO plans are a good starting point for building the reference scenarios within the model.

Finally, in conjunction with the previous point, from the technical perspective, the model needs to be thoroughly validated on historical data. In our case, the main validation metric to be passed is the model's ability to replicate electricity market price statistics for selected base years. To this extent, it should also be capable to showcase the electricity market price shocks which were experienced particularly harshly in the Baltic states in 2022. This is in contrast to limiting validation to "normal" or historically stable data. Additionally, the trade flows with other countries are of interest for validation. This is because limiting the geographical scope invariably causes complications in this regard, thereby the approach how to handle external flows needs to be selected based on thorough testing and validation.

B. Modelling Requirements

Due to the desynchronisation, local balancing resources will have significantly higher importance in Baltics from 2025 when FCR and aFRR markets will be established. Because of this, it is necessary and useful to model reserve markets explicitly (and not just as a part of generation/load earmarked for reserves). There is a concern of balancing resource insufficiency in the Baltic states. Large conventional generation sources might have to compete with newly built large-scale BESS. This will impact also the composition of units participating in the wholesale markets, thus we need a more elaborate co-modelling of balancing and wholesale markets. Balancing markets in Baltics are particularly prone to market power as they depend on few large providers. On the other hand, better unlocked flexibility might to some extent alleviate this. Therefore, this is one of the key topics to be addressed by the model.

Electrification of the transport and heating sector is another major issue which needs to be addressed in the model explicitly since it not only increases the total electricity demand but also offers additional flexibility which can conceivably be utilised in the markets in a number of ways. As of now, from within open-source models of the Baltic power system only [29] considers demand-side flexibility albeit with a simplistic assumption that 10% of the average demand is shiftable by up to 4 hours. While the lacking representations can be motivated by the historically low elasticity of the aggregate demand curve, demand response (DR) is gaining importance and should be considered more thoroughly and accurately in future modelling efforts. Moreover, regulatory matters strongly influence how DR can be marketed, and thus also the respective modelling assumptions. Due to this, the model has to be very versatile in its approach to modelling DR. For instance, we might want to model independent aggregator (IA) as a distinct market player (possibly participating in both supply and demand side), whereby regulatory rules dictate its relationships with other actors (suppliers, consumers) and thus affect the model. The model must be flexible and sophisticated in how it approaches IAs and other DR topics, so that we can study the consequences of regulatory choices regarding them.

A particular attention in the model is to be given to the Daugava hydropower plant (HPP) cascade. It comprises three hydraulically linked HPPs which supply 30–50% of the electricity consumed in Latvia (depending on the annual inflow). Being highly flexible run-of-river and poundage HPPs, they have limited but very valuable storage capacity, but their operational capabilities are additionally dependant on their time-delayed hydraulic linkage. These HPPs have a major impact on the electricity prices in the region and it is expected to only increase as is the penetration of intermittent generation.

In addition, the model is expected to reflect the imbalance settlement period to be switched to 15 minutes in foreseeable future in the Baltics. This essentially sets the minimum time resolution of the model. A high temporal resolution is additionally required in order to consider the impact of forecast errors in a future VRE-dominated power system and accurately model the balancing market operation.

Finally, as the model indeed primarily strives to study electricity market issues, there is a need to be able to reflect the specifics of bid preparation in various markets. This also includes, to the extent that is computationally reasonable, the inclusion of complex bid types e.g. in the day-ahead market. Such a necessity is motivated by practical considerations mainly driven by the relatively small size of the Baltic power system, whereby the actions of each large market actor can have major, sometimes unintended consequences. E.g. on 17 August 2022, the Baltic states reached a record high maximum day-ahead price at least partly due to overly large block bids which had to be paradoxically rejected [34]. The impact of bidding strategies and practices is indeed a crucial topic to be addressed by the model under development.

V. Conclusion

Recently, openness in energy modelling has become more widespread as it can improve scientific quality, enable more effective collaboration and facilitate stakeholder engagement. Hence, open source approach has been also selected for development of the Baltic electricity market model. While there is a wide range of already existing open-source modelling tools for energy systems and markets employing different approaches, only a few have been used for studying the issues relevant to the Baltic states in detail. Development of a model tailored for the Baltic states is crucial not only in light of the ongoing energy transition but also due to the approaching synchronisation with Continental Europe. The requirements for the Baltic model devised in this paper will inform the further efforts of our study. Ultimately, the electricity market model will be utilised to assess and inform the future development of electricity markets to facilitate energy transition and improve energy security.

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