Open source modeling for planing sustainable power development in resource-rich economies: case study for Kazakhstan

Ekaterina Fedotova[1*], *Ekaterina* Voronkova[2], *Davide* Fioriti[3], and *Maximilian* Parzen[4]

[1]Global Energy Problems Laboratory, Moscow Power Engineering Institute, 111250 Moscow, Russia
[2]Department of High Voltage Engineering and Electrophysics, Moscow Power Engineering Institute 111250, Moscow, Russia
[3]Department of Energy, Systems, Territory and Construction Engineering, University of Pisa, 56122 Pisa, Italy
[4]Institute of Energy Systems, University of Edinburgh, EH9 3DW Edinburgh, United Kingdom

Abstract. Power sector decarbonization is currently seen as a necessary condition of sustainable development in the modern world. options of resources-rich economies. Energy modeling is an effective measure to elaborate long-term decarbonisation policies. However, energy modeling evidence available for resources-rich economies remain up to the date limited, especially in part of realistic representation of the power system operation. We apply open code and open data approach to fill this gap considering a case study for Kazakhstan power system. The modeling input datasets have been validated against independent data sources with a satisfactory result. The simulation outputs are plausible both in terms reproducing the main features of the "pragmatic" scenario and in providing useful insights for the implementation of net-zero pathways. Renewable energy sources have been found to be economically viable even under the considered "pragmatic" scenario with quite conservative assumptions. Existing coal generation has been shown to dominate the investments costs hampering implementation of renewable power. A role of the power interconnection has been demonstrated for an economically optimal generation mix and a level of marginal electricity costs across the country. The results are intended to support energy transition implementation in the resources-rich economies under realistic technological assumptions.

1 Introduction

Coordination of the research and development efforts across the world is crucial for building sustainable future. That holds in particular for the climate mitigation targets and the energy transition pathways where the success may be only global.

Effective and inclusive approaches towards cross-regional and cross-national collaboration belong to the free and open software development just by design. That determines relevance of open source modeling for energy planning problems and has head to

---

* Corresponding author: e.v.kasilova@gmail.com

a rapid increase of open energy models and datasets throughout previous few year. The situation remains quite uneven and fragmented across the world [1] while need for detailed energy modeling is increasing along with progress of the energy transition around the world.

Kazakhstan is nowadays seen as a country having a strategic role for future energy supply in the Northern Eurasia. That is linked with the country's geographical location, fossil fuel reserves [2] as well as availability of the mineral resources which are critical for implementation of the energy transition [3], [4].

High wind and solar potential is typical for the most area of Kazakhstan which is combined with water-energy nexus issues [5] and generally rather harsh climate conditions. Under such circumstances, ambitious yet realistic national decarbonization goals determine a development vector which will likely give benchmarks for sustainable growth.

Apart of evident direct practical importance, there are fundamental research questions which can be addressed with better understanding the potential energy transition pathways in Kazakhstan accounting for the current constraints.

There are a few published works focused on modeling of the Kazakhstan power system. The most comprehensive modeling work [6] introduces a realistic model of Kazakhstan power system but don't consider decarbonisation options. In contrast, analysis [7] gives a detailed view on plausible decarbonization pathways for Kazakhstan power sector but doesn't account for spatial features of the power system. However, spatial structure and in particular transmission constraints have been shown to be have significant impact on power modeling results. Work [8] gives an insight into the spatial input data needed to build an energy model for Kazakhstan, but utilizing modeling was out of scope of this work. To the best authors' knowledge there is still no energy system model for Kazakhstan which would consider decarbonisation options. That implies limited understanding of the available implementation pathways for decarbonization options of Central Asia.

2 Contribution

Our work aims to start filling the identified knowledge gap by development a power system model for Kazakhstan considering realistic power grid topology and transmission constraints. Given the limited availability of the needed input data, we have decided to relying exclusively on open source code and open to ensure reproducibility of the developed data kit and model. The work contributions are:

1) extraction, pre-processing and validation a dataset needed for energy system modeling of Kazakhstan;

2) to develop the first open source energy model of Kazakhstan;

3) investigate decarbonization options for Kazakhstan power system accounting for existing power grid topology and transmission constraints.

The rest of the paper is organised as follows. The next section explains the used methodology for data preparation and modeling. Validation results are presented in Section 4. Modeling results are being discussed in Section 5 followed by the Conclusion.

3 Methodology

The main challenge towards the open energy models development remain data availability and quality which are still problematic for many regions of the world. A natural approach to overcome this obstacle is development of a universal modeling framework which combines an automated data processing workflow with the modeling procedures and can be adjusted to represent the region of interest. That is the motivation behind ongoing development of the PyPSA-Earth modeling software [9]. The software provides a toolkit to simultaneously optimize the operation and optimal investment for a regional power system over multiple periods. Modeling workflow integrates data extraction and pre-processing which implies linking of multiple data sources and open-source tools to process raw data, e.g. OpenStreetMap for transmission grid data.

PyPSA-Earth belongs to a class of optimization energy system models. That implies minimization the overall costs of electricity taking into account options on generation and transmission expansion [9], [10] under the assumption of a partial-equilibrium market.

4 Validation

The main model inputs were compared against the independent third-party data sources to make sure that the model adequately reflects the major parameters of the national power system.

4.1 Transmission network

The grid topology (Fig. 1) corresponds well to the data provided by the Kazakhstan Electricity Grid Operating Company (KEGOC) [11] and the Global Energy Networks Institute [12]. It also matches to [8] with the only major difference in the transmission line in the eastern part of the country. The reason of this difference is that construction of this line has been completed after [8] was published.

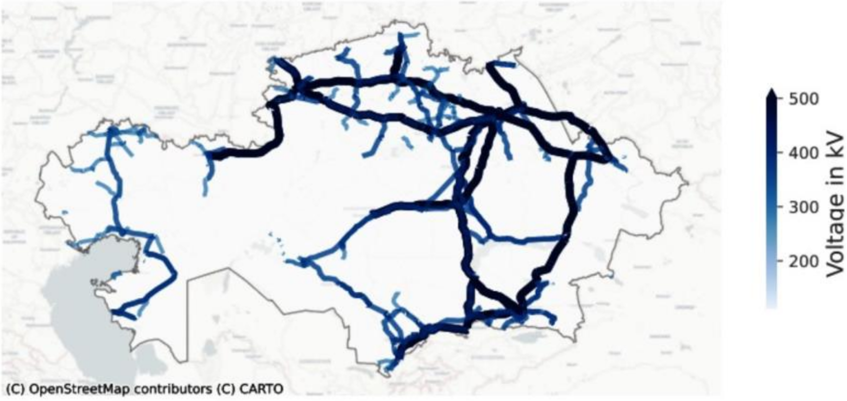

Fig. 1. Representation of the network grid topology extracted and pre-processed by the workflow.

Qualitative validation by the lines length has revealed mismatch between the modeled network and KEGOC data while the former is fully consistent with World Bank Data. A likely reason of the found discrepancy is some non-trivial assumptions behind KEGOC re-calculation between a circuits length and a line length.

Table 1. Validation of transmission network length (km) of Open Street Map data against World Bank data

	220 kV	500 kV	1150 kV
Open Street Map (raw)	35657	16671	1737
Open Street Map (clean)	31729	12464	1737
World Bank	29402	12661	2260

Further validation has relayed on World Bank Data. The estimated discrepancy of the transmission network length was about 2% and 8% for 220 kV and 500 kV lines, respectively and as high as 30% for 1150 kV lines.

4.2 Installed capacity

The overall installed capacity extracted with the modeling workflow is 19.47 GW with share of coal generation comprising 72%. The national Ministry of Energy provides data on installed capacity for 2020 being 22.9GW overall value and 19.3GW available capacity [13], respectively. The International Renewable Energy Agency (IRENA) gives estimations for the installed capacities increasing from 21GW in 2014 to 27GW 2021 [14].

The modeled capacity values are lower as compared with the both reference datasets. That is likely connected with the fact that the modeled data do not capture recent changes in the national power generation fleet which took place throughout few last years. In particular, that means that gas-fired generation can be under-estimated by the model.

4.3 Power demand

Validation of the electricity demand has been fulfilled for three selected years: 2011, 2013 and 2018. The electricity demand has been calculated by [15] approach and compared against the data provided by KEGOC [16] with annual and monthly resolution and aggregation by the national territory.

The validation results have shown that the modeled electricity demand matches well with the observed values on both considered time scales (Fig. 2).

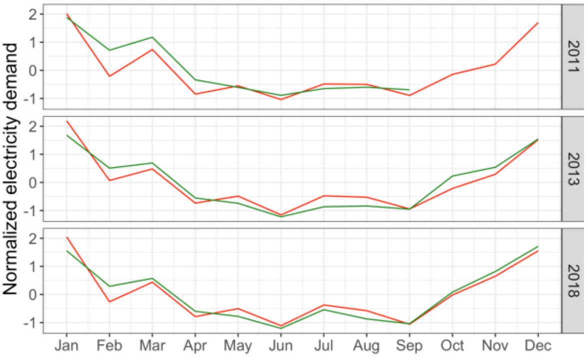

Fig. 2. Comparison of the monthly aggregated modeled input demand (red) with KEGOSC data (green). Data normalization implies subtraction of the mean and dividing on the standard deviation for each considered year.

5 Results

The model has been run for a pragmatic scenario to check plausibility of the modeling outputs. The scenario was intended to simulate power system operation on a few years time horizon under a condition there will be no dramatic changes in the national energy policy (like carbon tax or regulative restriction of greenhouse gases emissions). The following assumptions have been taken:

- the parameters of generation, storage and transmission technologies have been assumed to correspond a prospective level of 2030;
- the electricity demand set according to ssp2-2.6 socio-economic conditions;

- expansion of wind, solar and open cycle gas turbines is allowed during optimization along with implementation of batteries and hydrogen as storage technologies.

Spatial clustering has been applied to tackle the computational complexity of solving a co-optimization problem of transmission and generation capacity expansion. A clustering procedure select sets of nodes that are similar and aggregates them to a single node representing the original set. This way, the network is reduced to a smaller number of nodes to manage the model's computational complexity.

5.1 Spatial structure

Distribution of the power flows across the transmission lines is consistent with [6] findings (Fig. 3). However, application of the clustering approach has obviously led to reduction of the power system structure.

Fig. 3. Annual average utilization of the transmission lines.

In particular, the modeled power system implies the following simplification:

- some supply and demand nodes have been merged (e.g. Astana, Qaraghandy and Pavlodar were represented with a single bus);
- west of the country have been modeled as an isolated network which is a consequence of neglecting with cross-boundary power flows;
- masking high utilization of the transmission lines on some network sections (e.g. on the network section south of Atyrau, see [6] for comparison).

During an optimization run, we perform a brownfield capacity expansion optimization. This means new renewable energy and transmission capacity can be built on top of existing infrastructure if it is viable from an economical point of view. The optimization objective is to minimise the total annualized costs of the system comprised of the annualised capital and operational expenditures. Simultaneously, a dispatch optimisation is performed subject to linear optimal power flow constraints.

The objective function is subject to multiple linear constraints [9] to make scenarios more realistic giving a convex linear programming problem with continuous variables. Firs of all, the energy balance is guaranteed by using the demand equals supply constraint. Geophysical and operational constraint for generators, storage units as well as power lines are being implemented to represent operation of the power system in a realistic way. Kirchhoff's current and voltage equations are being used to represent the physics of electric energy flows in the power network.

The model run has resulted in an output that renewable generation is still economically viable even under the considered conservative scenario (Fig. 4).

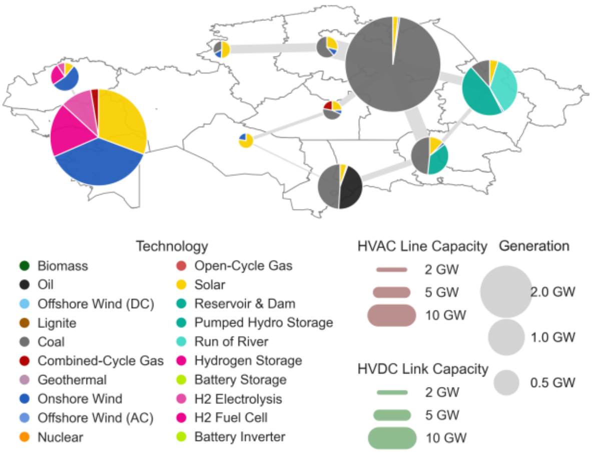

Fig. 4. Optimization results for the installed capacity corresponding to the pragmatic scenario for Kazakhstan power system. The colored points represent structure of the installed capacities.

5.2 Discussion

Analysis of the modeled dispatch shows a trade-off between effective operation of conventional generators and development of renewable power. Introducing renewable generation into the power system obviously leads to a drop in capacity values of the fossil-fuelled generation. Apart of that, an increasing share of intermittent renewable power lead to an increasing demand in balancing power. All the mentioned effects are well known from operation experience of the power systems. Economical outputs of the model optimization run results in a conclusion that the highest capital expenditures should be expected for coal plants (Fig. 5).

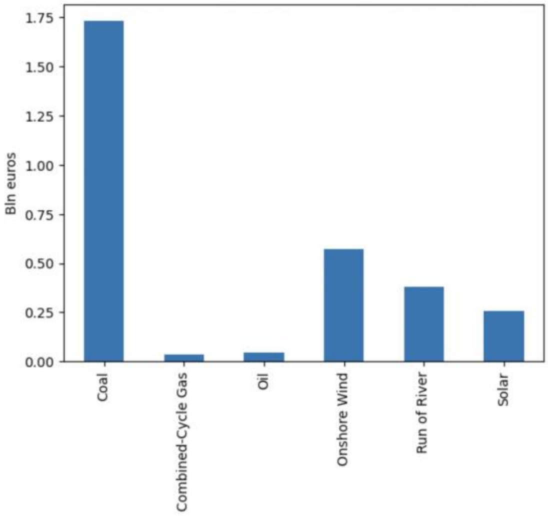

Fig. 5. Simulated capital expenditure by technologies corresponding to the pragmatic scenario for today's Kazakhstan power system.

When interpreting this result, it should be noted that the model does not account the actual age of the generation fleet. In some cases the power plants are operating for more that eighty years which is about four times higher as compared with the lifetime values assumed in the model. Some adjustments of the model inputs could be beneficial to account for this ageing effect more accurately. However, even in the current basic modification, the model results clearly indicate that having in the power system a lot of new coal power plants can be a serious obstacle towards development of renewable generation.

5.3 Limitations and further work

In the course of validation, it has been shown that while the model adequately reflects the main features of the power system in general, the data on the installed generation should be updated. The model run has demonstrated that this limitation has significantly influenced optimization results on the optimal capacity mix for the western part of the country.

Regarding the model structure and assumptions, the following improvements can be considered in future work.

1. Representation of combined heat and power plants can be introduced. This point is less relevant for the net-zero scenarios but crucial for modeling the state of the power system along the decarbonization path.
2. Trans-boundary power-flows can be included into consideration. That can be achieved quite easily by increasing the modeled domain.
3. The economical parameters can be revised to account for regional specifics in a more proper way.

6 Conclusion

The presented work might be summarized as follows. The developed model is a successful proof-of-concept of open source energy modeling for Kazakhstan which is based solely on the open data. It has been found that the developed modeling inputs data kit well correspond to independent datasets available for the region.

A simulation done for a considered “pragmatic” scenario has shown that the existing coal plants can hamper the energy transition due to significant investments costs, especially if these plants were commissioned recently. Transmission constraints were found to strongly influence energy modeling outputs meaning that decarbonisation plans should necessarily account for realistic power transmission options.

7 Acknowledgment

Authors are very grateful to the whole PyPSA community for constant support and collaboration. E.Fedotova and E.Voronkova also thank Dr. S.M. Krasheninnikov and Eng. Ju.A. Kozlova for highly inspiring discussions. E.Fedotova and E.Voronkova gratefully acknowledge financial support provided by the Russian Science Foundation (project no. 18-79-10255).

References

1. OpenMod: Open model implementations. Available via https://wiki.openmod-initiative.org/wiki/Open_model_implementations [access 12.02.2023].
2. G. Cassetti, A. Elia, M. Gargiulo and A. Chiodi, “Reinforcing the Paris Agreement: Ambitious scenarios for the decarbonisation of the Central Asian and Caspian region,” *Ren. and Sust. Energy Trans., vol.* 3, pp. 100048, August 2023.

3. R. Vakulchuk and I. Overland, “Central Asia is a missing link in analyses of critical materials for the global clean energy transition,” *One Earth*, *vol.* 4, *i.* 12, pp. 1678-1692, December 2021.
4. A. Tleubergenova, Y. Abuov, S. Danenova, N. Khoyashov, A. Togay and W. Lee, “Resource assessment for green hydrogen production in Kazakhstan,” *Intern. Jour. of Hydr. En.*, June 2022.
5. B. Zakeri, J. D. Hunt, M. Laldjebaev, V. Krey, A. Vinca, S. Parkinson and K. Riahi, “Role of energy storage in energy and water security in Central Asia,” *Jour. of En. Stor.*, *vol.* 50, pp. 104587, June 2022.
6. M. Assembayeva, J. Egerer, R. Mendelevitch, and N. Zhakiyev, “A spatial electricity market model for the power system: The Kazakhstan case study,” *Energy*, *vol.* 149, pp. 762-778, April 2018.
7. D. Bogdanov, A. Toktarova and C. Breyer, “Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan,” *Appl. En.*, *vol.* 253, pp. 113606, November 2019.
8. M. Assembayeva, J. Egerer, R. Mendelevitch, and N. Zhakiyev, “Spatial electricity market data for the power system of Kazakhstan,” Data in Brief, vol. 23, pp. 103781, April 2019.
9. M. Parzen, H. Abdel-Khalek, E. Fedotova, M. Mahmood, M. M. Frysztacki, J. Hampp, L. Franken, L. Schumm, F. Neumann, D. Poli, A. Kiprakis and D. Fioriti, “PyPSA-Earth. A New Global Open Energy System Optimization Model Demonstrated in Africa” Appl. Energy. (2022).
10. T. Brown, J. Horsch and D. Schlachtberger, “PyPSA: Python for Power System Analysis,” *Jour. of Open Res. Softw.*, *vol.* 6, pp. 1-10, July 2017.
11. Map of Kazakhstan power system provided by KEGOC https://www.kegoc.kz/upload/files/karta-skhema-ees-rk-2023-ru.pdf (access 23.04.2023)
12. Map of Kazakhstan power system provided by Global Energy Network Institute http://www.geni.org/globalenergy/library/national_energy_grid/kazakhstan/kazakhstaniannationalelectricitygrid.shtml (access 19.03.2023)
13. Official site of Kazakhstan Ministry of Energy https://www.gov.kz/memleket/entities/energo/activities/215?lang=en (access 23.04.2023)
14. IRENA (2022), Kazakhstan energy Profile 2022, International Renewable Energy Agency, Abu Dhabi
15. A. Toktarova, L. Gruber, M. Hlusiak, D. Bogdanov, C. Breyer, “Long term load projection in high resolution for all countries globally”, *Int. Jour. of El. Pow. and En. Syst.*, *vol* 111, pp. 160–181, October 2019.
16. KEGOC, 2023. Available via: https://www.kegoc.kz [access 23.04.2023].