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Comprehensive Scenario Analyses for Coal exit and Renewable Energy Development Planning of Kazakhstan using PyPSA-KZ

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Abstract

This article focuses on the application of Python for Energy System Analysis (PyPSA) in modelling future energy scenarios for the Kazakhstan's energy system. The study addresses the challenges inherent in Kazakhstan's energy sector and explores how PyPSA can play a pivotal role in supporting the country's transition to sustainable, green energy. In this paper, the PyPSA-KZ model of Kazakhstan power system is proposed for accurate energy modeling and investment planning for the period up to 2040. The model is adapted considering the characteristics of Kazakhstan's power plants, hourly demand profiles for each administrative zone, and marginal electricity generation costs for each power plant and cost of each energy carrier. Validation of the model is carried out by running the Business-as-Usual scenario for 2020 and comparing the results with official reports. After validation, three investment scenarios are studied: i) renewable energy with 30% share, ii) coal exit scenario, and iii) 30% RES share with transmission line expansion, followed by determining the cost-optimal solution for 2040. Across all scenarios, emphasis is placed on increasing the contribution of wind and solar energy. The outcomes of the scenario modeling hold significant implications for policy formulation, effective energy management, and strategic investment planning in Kazakhstan.

Keywords: Power system modeling; PyPSA-Earth; PyPSA-KZ; Spatial modeling; Renewable energy.
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1. Introduction

Kazakhstan, as one of the major fuel and energy production countries in the Central Asian region, targets net carbon neutrality by 2060.[1] The availability of vast coal resources with a low production cost and developed transportation infrastructure makes coal a dominant source of energy. However, to achieve net-zero goals, the energy sector of Kazakhstan plans to transition from coal-fueled to more environmentally friendly gas and renewable energy-based energy production. In particular, it is planned to reduce the share of coal-based electricity generation from 69% (in 2020) to 40% by 2030, while the share of electricity generation by renewable-based carriers and natural gas is planned to be increased to 24% and 25% by 2030, respectively. In addition, it is aimed to reduce the greenhouse emission to pre-1990s level by 2030.[1]

A recent technical report[2] indicate that the electricity generation sector of Kazakhstan reached 23.96 GW of installed capacity, 82% of which are thermal power plants operated on coal (13.4 GW) and gas (6.05 GW). The available power, however, is limited to around 19 GW.[3] The bulk of thermal power plants (*i.e.* 41 out of 68) are combined heat and power plants (CHPP) that provides both electricity and district heating.[4] The importance of CHPPs in the energy sector of Kazakhstan is undeniable as they play a crucial role in

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maintaining urban infrastructure amidst the harsh continental climate. In terms of renewable energy carriers, 40 small hydroelectric power plants (HPP) with 280 MW, 40 wind power plants (WPP) with 6894 MW, 49 solar power plants (SPP) with 1038 MW, and 8 biomass-fueled power plants with 8 MW installed capacity operate in Kazakhstan.[2] The transmission line infrastructure consists of 220, 500, and 1150 kV high voltage (HV) lines. The entire electricity grid is divided into three zones, namely the North, South, and West zones.[2] The Fig. 1, illustrates the power system network of Kazakhstan partitioned into three distinct zones.

To contribute to the achievement of carbon neutrality by 2060, the electric power sector of Kazakhstan needs to address several significant challenges. The first major issue is associated with excessive wear of electricity infrastructure (around 50-70%) which negatively affects the efficiency and stability of the grid. A large fraction of CHPPs were built during the Soviet era and need significant modernization.[1] Another critical issue that requires rigorous consideration is significant energy losses (around 8.3%) in power transmission due to large transmission distances and equipment wear.[1] In addition, the distant location of generation and consumption units makes power system angular stability a significant concern, particularly in Kazakhstan. The next important issue is an imbalance between generation and consumption by regions. In Kazakhstan, the majority of the generation capacities are situated in the North, while the South is electricity deficient; the West region is not physically connected to the rest of Kazakhstan’s grid.[1] Such local peculiarities of the electricity grid signify the importance of accurate spatial energy modeling and thoughtful placement of renewable energy source (RES) power plants. Moreover, with the commissioning of RES power plants, the necessity for balancing power with conventional dispatchable power plants rises. The current CHPPs cannot be fully utilized for power balancing as they operate based on the thermal schedule and are generally incapable of rapid change of power output without equipment stress and wear.[5] Hence, the necessity for the development of a meticulous investment plan for the construction of additional conventional electricity-only power plants for power balancing rises. Furthermore, a recent global boom in cryptocurrency mining put considerable stress on the electricity system of Kazakhstan, as Kazakhstan became one of the leading countries in bitcoin mining (around 18.1% of global bitcoin production[6]) due to low electricity prices and loose policies. To be specific, the estimated total electricity consumption of digital mining centers is beyond 1000 MW, not including the consumption of shadow mining.[2] Finally, the impact of the electricity cost on social stability is a crucial factor that requires rigorous consideration.[1] Therefore, an accurate spatial and time domain modeling of the electricity and energy system of Kazakhstan is essential for the attraction of investments to the generation sector and ensuring reliability and affordability of electricity and heat supply.

In past decades, extensive research was conducted to analyze and model the energy sector of Kazakhstan. In Ref. [7], a model of regulatory stability was developed, regulatory stability criteria were defined for the state, which can comply with them when reforming schemes for supporting projects related to renewable energy sources. Next study with the model constructed with the help of LUT Energy System Transition modelling tool was analyzed,[8] it investigated the transition of electricity and heat supply systems to 100% renewable energy sources. Refs. [9] and [10] propose an optimization strategy for the largest CHPP of Kazakhstan by planning energy generation and maintenance simultaneously that may result in 85%, 15%, and 13% reduction in startup/shutdown, fuel, and fixed costs, respectively. An overview of the current condition of the energy system of Kazakhstan is presented in Ref. [11] with a detailed SWOT analysis. A comprehensive spatial modelling of Kazakhstan's electricity system is proposed in Refs. [12] and [13]. The model includes unit-commitment functionality and estimates nodal and zonal pricing of electricity for winter and summer period with hourly resolution using publicly available data. In addition, the model considers cross-border electricity transmission, line losses, and generation constraints of CHPPs. The study[14] identified and explained the main facts of electricity loss, the causes of inefficient energy distribution within the country, investigated the impact of administrative barriers on the sustainable development of enterprises in the field of electric power. Ref. [15] summarizes all recent changes and major issues in the energy sector of Kazakhstan. The potential risks of large-scale RES integration to the electricity system of Kazakhstan are discussed in Ref. [1]. In Ref. [16], the authors deliberate on the key challenges of the regional and national integration of RES by considering the Almaty region (South-East Kazakhstan) as a case study. The work highlights the importance of balancing electricity supply and claims that a centralized outdated top-down management system and the absence of decentralized consumption options are the primary obstacles to RES integration.[17] This work evaluates the renewable energy policy of Kazakhstan and underlines the importance of not only post-investment regulation but also pre-investment flexibility to support regularity and stability.

By taking into consideration different aspects of Kazakhstan's energy sectors the previous study has explored

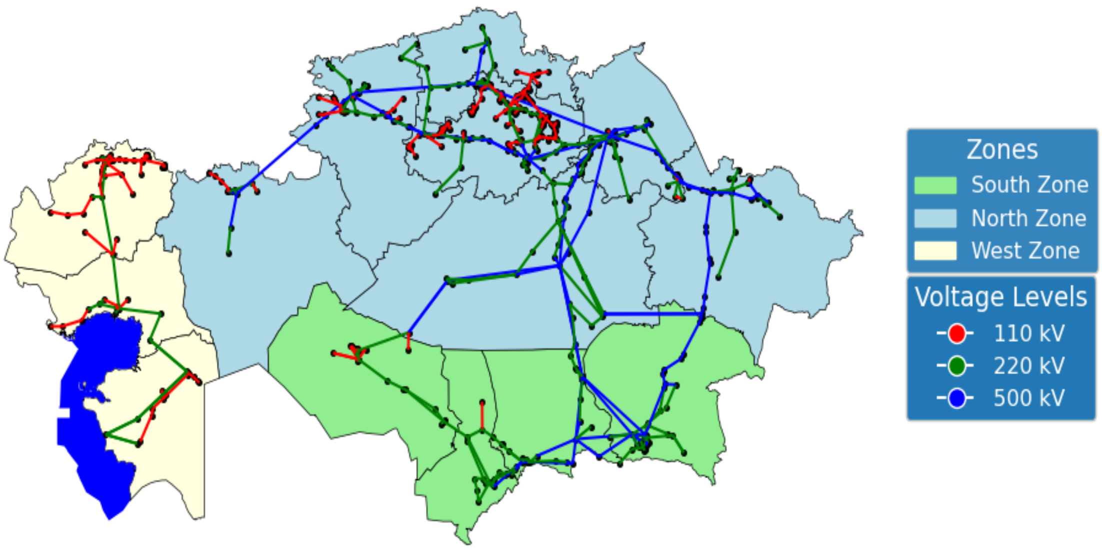


Fig. 1 Power system network of Kazakhstan.

many things - from bottom-up energy modeling approaches to optimization strategies for CHPPs. However, the main challenge remains integrating the results into a comprehensive model that will help guide Kazakhstan's transition to a green economy. In order to address this problem, this study has undertaken a pathway to present a comprehensive energy model of Kazakhstan (PyPSA-KZ). By taking into account tools such as PyPSA, in line with the specificities of Kazakhstan's energy landscape, we offer stakeholders especially policy makers and investors a holistic perspective, providing them with useful knowledge for energy and investment planning up to 2040.

Comprehensive nationwide energy modeling is a key factor in the stable and cost-effective operation of a power grid. Accurate modeling of the national energy system facilitates tackling an energy-forecasting problem and achieving sustainable goals. In this regard, development and validation of an open-source energy model are crucial for effective management and transparent policymaking. In recent years, among various free open-source solutions, Python for Power System Analysis (PyPSA).[18] PyPSA stands out with its open-source code, flexible tools for modeling various aspects of electric power systems, and seamless integration with economic models has a number of advantages for modeling an energy system. In contrast to other energy system models, such as DIgSILENT PowerFactory,[19] MATPOWER,[20] which are limited to single-sector power simulation, and multiple-sector models like Calliope[21] and OSeMOSYS Global[22] that use simplified energy networks and lack crucial components like unit-commitment and power flow constraints, along with TIMES[23] built in GAMS, restricting free use and lacking open-source accessibility, PyPSA offers a unique combination of high spatial and temporal resolution. PyPSA's capabilities extend beyond the power sector, making it a comprehensive solution for holistic energy system analysis. Thus, it emerges as a versatile and robust choice for energy system modeling and analysis. Table 1 below compares various functionalities among widely adopted energy system models, providing a quick reference to their respective strengths and limitations.

Within the PyPSA framework, two major models, namely PyPSA-Eur[3] and PyPSA-Earth,[24] are currently on active development. The former models the entire European energy system, while the latter focuses on global energy modeling using publicly available open-source data. Out of these two PyPSA models, PyPSA-Earth draws significant research interest as it enables region-level and country-level electricity

Table 1. Comparison of specific characteristics in energy system models.

Software	Free and open source	Multi Sector Model	Power flow Calculation	Optimal power flow	Unit Commitment
DIgSILENT			+	+	+
MATPOWER	+		+	+	+
Calliope	+	+			+
OSeMOSYS TIMES	+	+		+	+
PyPSA	+	+	+	+	+

system modeling outside of the European Union.[24] The Central Asia region, in particular Kazakhstan, is geographically covered well by PyPSA-Earth model. Development and fine-tuning of PyPSA-Kazakhstan (PyPSA-KZ) as an integral part of PyPSA-Earth package using locally available energy data will help to improve the PyPSA-Earth model and validate the effectiveness. On the other side, the well-established PyPSA-KZ model facilitates a transition of Kazakhstan to a green economy by reducing electricity-related greenhouse emissions. In particular, rigorous energy system model will help to minimize electricity cost, meet future energy demands, and modernize the existing energy infrastructure.

This study raises topical issues related to the energy sector of Kazakhstan, analyzes the compliance of current policies and measures with the ambitious goals of the country to achieve carbon neutrality and transition to a green economy. Moreover, the potential of such tools as PyPSA, which can help the country in this transition, is revealed, namely, a quantitative assessment of the effectiveness of these measures is prescribed based on PyPSA modeling, taking into account various scenarios. In addition, it examines the optimal distribution of renewable energy sources within Kazakhstan and quantifies the indicators of this distribution based on PyPSA modeling, including prospects for increasing current targets by 50%. Finally, the problems inherent in the energy landscape of the country are investigated, and how these problems can be overcome with the help of advanced modeling methods. In the article, the authors put forward several hypotheses. Firstly, it suggests that the adaptation of the PyPSA-Earth model for Kazakhstan could provide invaluable information that will help the country cope with its energy problems and successfully switch to renewable energy sources. Secondly, it postulates that through careful spatial energy modeling and strategic placement of installations for the use of renewable energy sources, it is possible to eliminate regional differences in energy production and consumption in Kazakhstan. In conclusion, the study underscores the potential benefits of revitalizing Kazakhstan's aging energy infrastructure while integrating cutting-edge energy models, which could significantly reduce energy wastage and enhance the efficiency of the national energy grid. The model in this paper is customized and validated using data provided by the local electricity provider for 2020. Three investment scenarios: i) renewables only, ii) renewables coupled with line investment, and iii) renewables with both storage and line investment are considered and the optimal cost scenario is determined. The simulation scenarios cover a one-week period in both winter and summer seasons, which represented the maximum winter and minimum summer demands. For each scenario, the total investment cost, ultimate energy mix, and optimal allocation of RES power plants are determined. Optimal line investment results are provided for both Scenario II and III, while the optimal allocation of storage units is identified for Scenario III.

The rest of the paper is organized as follows. Section II introduces the background information on the PyPSA framework and PyPSA-Earth model in detail, an implementation of PyPSA-KZ and model validation are presented in Section III. In Section IV, three aforementioned investment scenarios are investigated and compared followed by Conclusion in Section V.

2. PyPSA framework

2.1 PyPSA

PyPSA is an open-source software toolbox developed for simulating and optimizing electrical power systems over multiple time periods with investment capabilities.[25] It features models for traditional generators with unit commitment, renewable energy sources with variability, energy storage units, interconnection with other energy sectors, and a mix of alternating (AC) and direct current (DC) networks.[25] PyPSA is designed to be scalable and extendable for large networks and extended time series. PyPSA serves as a link between steady-state power flow analysis tools and comprehensive multi-period energy system models while being free software.

PyPSA is capable of optimizing the linear power flow equations to address both short-term operational needs and future energy system investments.[25] This is achieved through a linear approach, encompassing both short-term management and long-term strategic planning. Optimization in PyPSA is performed by minimizing the total system cost by solving linear optimal power flow (LOPF) equations. The objective function is defined using variable and fixed costs for electricity generation, transmission, and storage, as well as physical and technological constraints. The total system cost is given as:[25]

$$\min_{\substack{F_l, G_{n,r}, H_{n,s}, E_{n,s}, f_{l,t}, g_{n,r,t}, \\ h_{n,s,t}, suc_{n,r,t}, sdc_{n,r,t}}} \begin{bmatrix} \sum_l c_l \cdot F_l + \sum_{n,r} c_{n,r} \cdot G_{n,r} + \\ + \sum_{n,r,t} \left(w_t \cdot o_{n,r} \cdot g_{n,r,t} + suc_{n,r,t} + sdc_{n,r,t} \right) + \\ + \sum_{n,s} c_{n,s} \cdot H_{n,s} + \sum_{n,s} \hat{c}_{n,s} \cdot E_{n,s} + \sum_{n,r,t} w_t \cdot o_{n,s} \cdot \left[h_{n,s,t} \right]^+ \end{bmatrix},$$

where l represents branch label; n is a bus label; r is a carrier label for the generator; t is a time; s is carrier label of storage unit; c_l and F_l are capital cost and active power rating of the branch; $c_{n,r}$ and $G_{n,r}$ are capital cost and power capacity of generation for carrier r at bus n; w_r is a snapshot weightings; $g_{n,r,t}$ and $o_{n,r}$ are dispatch of generator with carrier r at bus n in time t and dispatch cost; $suc_{n,r,t}$ and $sdc_{n,r,t}$ are generator startup and shutdown costs; $c_{n,s}$ and $H_{n,s}$ are capital cost of power and power capacity of storage at bus n; $\hat{C}_{n,s}$ and $E_{n,s}$ are the capital cost of energy and energy cost of storage at bus n; $o_{n,s}$ and $[h_{n,s,t}]^+$ are storage dispatch cost and positive part of storage unit dispatch at bus n, respectively; and $f_{l,t}$ is a flow at branch l at time t. The electricity demand $d_{n,t}$ at bus n in time t is supplied by generation, storage, or energy flows from other branch and the equation is expressed as follows,

$$\sum_r g_{n,r,t} + \sum_s h_{n,s,t} + \sum_l \alpha_{l,n,t} \cdot f_{l,t} = d_{n,r,t} \quad \leftrightarrow w_t \cdot \lambda_{n,t} \quad \forall n, t,$$

where $\alpha_{l,n,t}$ = 1 for line or transformer ending at bus n; for branch l starting at bus n, $\alpha_{l,n,t}$ = -1; and $\alpha_{l,n,t} = \eta_{l,n,t}$ for branches l that are links ending at bus n; $\lambda_{n,t}$ is the marginal price of electricity at bus n in time t. Equation (2) embodies Kirchhoff's Current Law (KCL), which ensures the preservation of energy at every node.

In addition to KCL, Kirchhoff's Voltage Law (KVL) is either applied in PyPSA to ensure the realism of the network flows. KVL asserts that the total voltage variations around any closed loop within the network must equate to zero. KVL in PyPSA is formulated as follows,

$$\sum_l C_{lc} \cdot x_l \cdot f_{l,t} = 0 \quad \forall c, t,$$

where c is an independent cycle, C_{lc} is a matrix containing a combination of each independent cycle c and passive branch l, and x_l is a series inductive reactance of branch l. The definition of the KVL with the aforementioned method helps to solve the equations 20 times faster while maintaining the same accuracy as voltage angle-based KVL formulation.[26]

In PyPSA, a transmission loss in LOPF is realized using a piecewise linear approximation of up to three tangents.[27] In particular, the loss is defined in the nodal balance equation as follows,

$$p_i = \sum_l K_{il} \,.\, p_l + \frac{|K_{il}|}{2} \Psi_l \qquad \forall_i \in N,$$

where p_i is the nodal power injection, K_{il} is the incidence matrix, p_l is the active power flow in branch l, N is the set of buses, and ψ_l is the power loss at branch l. In other words, the total loss of the branch is equally split between two buses and is defined as:[27]

$$\psi_l = r_l \cdot {p_l}^2,$$

where r_l is the resistance of branch l. This quadratic equation of the loss is approximated using tangents for evenly spaced segments.

2.2 PyPSA-Earth

The PyPSA-Earth model is an innovative open-source data management and optimization tool that is designed to assist policymakers, companies, and researchers in conducting various analyses related to macro-energy systems.[24] It is intended to serve as a common platform for these groups to work together towards achieving the transition to cleaner energy. The model allows for the creation of customized models on a national, continental, or global scale, all under a single code repository. At now, PyPSA-Earth facilitates modeling energy systems and simulation of various scenarios for the majority of world countries including Kazakhstan.

3. PYPSA-KZ

3.1 PyPSA

Within the PyPSA framework, various models have been actively developed, such as PyPSA-Eur and PyPSA-Earth.[3] The former models the energy system of Europe, while the latter focuses on the entire earth. In this work, we deploy PyPSA-Earth as a base model for the energy modeling of Kazakhstan. In general, the PyPSA-Earth model is an innovative open-source data management and optimization tool that is designed to assist policymakers, companies, and researchers in conducting various analyses related to macro-energy systems.[24] The model allows for the creation of customized models on a national, continental, or global scale, all under a single code repository. However, the off-shelf default PyPSA-Earth model has low accuracy in modeling and optimization of Kazakhstan's energy system due to outdated open-source data and assumptions. To resolve the issue, we have customized our model (PyPSA-KZ) using the data from recent national reports and up-to-date open sources. In particular, the customization of the model involved the utilization of annual electricity demand data per region from the national report,[1] current data of power plants,[28,29] capacities of transmission lines, and import/export data.[30]

To perform adequate investment planning for the future, it is crucial to accurately define the existing energy system and validate it by comparing it with the real reported data. For this purpose, the PyPSA-KZ model was built within the PyPSA-Earth repository and customized based on the aforementioned official data. The network was aggregated into 14 buses that represent 14 administrative regions of Kazakhstan. The demand profile for each administrative zone was scaled based on the annual demand provided in the national report.[1] The model was validated using data from 2020, which is the most recent year covered by the latest official national report.[1]

3.2 PyPSA-KZ model validation

To perform investment planning and model simulation for future scenarios, it is essential to validate the accuracy of the model on the existing network. This study considers 2020 as a base scenario for model validation. The Table 2 below provides an overview of the transmission network length in kilometers across different voltage levels, comparing data from the World Bank and the PyPSA-KZ model.

Table 2. Transmission network length in km.

	35kV	110kV	220kV	500Kv	1150kV*
World Bank	0	0	29402	12921	2260
PyPSA-KZ	2606	14103	31733	14201	0

*In Practice, 1150kVtransmission lines operate under 500kV.

Table 3 presents generation capacity in megawatts (MW) across various sources, utilizing data from IRENA,[31] a national report,[4] and default values in PyPSA-Earth. PyPSA-Earth default represents the default generation capacities of Kazakhstan in PyPSA-Earth, while PyPSA-KZ represents our customized model.

Table 3. Generation capacity in MW.

	IRENA[31]	National Report	PyPSA-Earth Default	PyPSA-KZ
Focus year	2020	2020	-	2020
Coal	19461.2	13407.0	14121.3	12967.0
Gas		6013.0	400.0	5105.4
OCGT	-	2015.0	0.0	1625.4
CCGT	-	3998.0	400.0	3480.0
Oil	-	0.0	1139.4	0.0
Hydro	2784.7	2734	3481.1	2726.0
Run of River	-	-	1395.0	62.8
Reservoir	-	-	2086.1	2663.2
Wind	486.3	509.0	429.4	648.7
Solar	911.6	958.0	1580.7	821.8
Total	23646.8	23621.0	21151.9	22268.9

For PyPSA-KZ, annual consumption was scaled based on the national report for each administrative region (Table 4).[1]

Table 4. Annual consumption in TWh.

	Our World in data[32]	National Report[4]	PyPSA-Earth Default	PyPSA-KZ
Focus year	2020	2020	2020	2020
Total	107.10	107.34	107.75	107.34

Table 5 shows the alignment of the administrative zones' annual energy consumption figures reported by PyPSA-KZ with those from a national report.[4] The table showcases that PyPSA-KZ adequately captures the regional variations in energy consumption, indicating its effectiveness in providing realistic estimations for different administrative zones.

Table 5. Annual consumption by administrative zones in GWh.

Administrative zone	National report[4]	PyPSA-Earth default	PyPSA-KZ
East Kazakhstan	9204	4910	9204
Karaganda	18460	7224	18460
Kostanay	4615	21819	4615
Pavlodar	20731	3894	20731
Akmola	9196	31154	9196
North Kazakhstan	1665	989	1665
Aktobe	6647	1468	6647
Almaty	11367	17850	11367
Turkestan	5211	4337	5211
Zhambyl	4948	2702	4648
Kyzylorda	1760	3098	1760
Mangystau	5023	1379	5023
Atyrau	6255	2645	6255
West Kazakhstan	2256	4282	2256
Total	107338	107752	107338

Comparison of PyPSA-KZ model simulated generation output with national report data indicates that PyPSA-KZ adequately represents the electricity generation from various sources, as shown in Table 6 below.

Table 6. Annual generation in GWh.

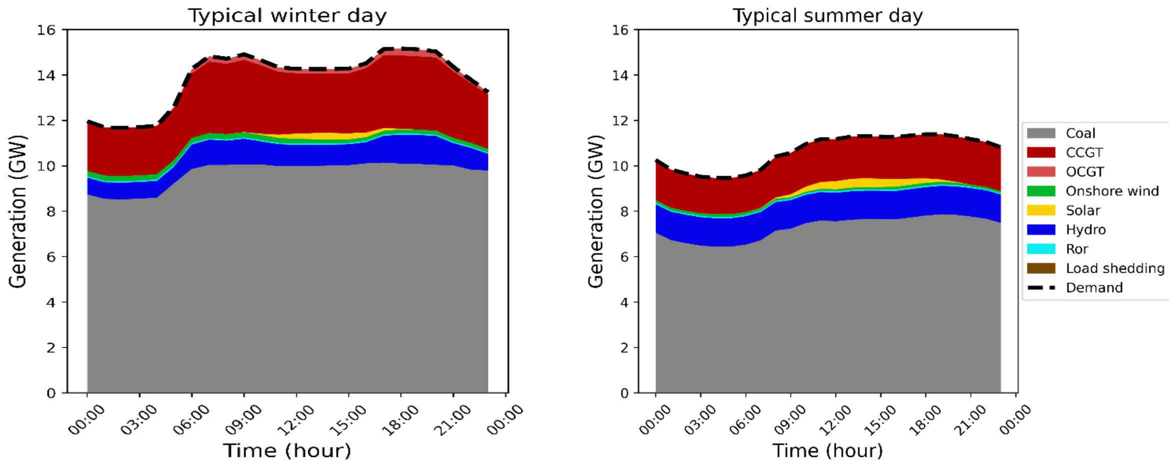
	National report	Base scenario
Focus year	2020	2020
Coal	74497.6	74573.0
Gas	21692.7	20359
Hydro	9545.8	10862.9
Wind	1092.7	1718.0
Solar	1252.1	1048.4
Total	108080.9	108591.3

4. Optimization Scenarios

Three optimization scenarios are considered: *i) Scenario 0*: Base scenario of 2020, *ii) Scenario 1*: RES share of 30%, *iii) Scenario 2*: Coal exit, and *iiii) Scenario 3*: New line with RES 30%

4.1 Scenario 0: Base scenario of 2020

Figure 2 illustrates the generation profiles for a typical winter (a) and summer (b) day in Scenario 0, representing the base scenario of 2020. The figure reveals that a significant portion of the energy mix is contributed by coal, combined cycle power plants, and hydropower.



(a) (b)

Fig. 2 Generation profiles for typical (a) winter and (b) summer day of Scenario 0: base scenario of 2020.

4.2 Scenario 1: RES share of 30%

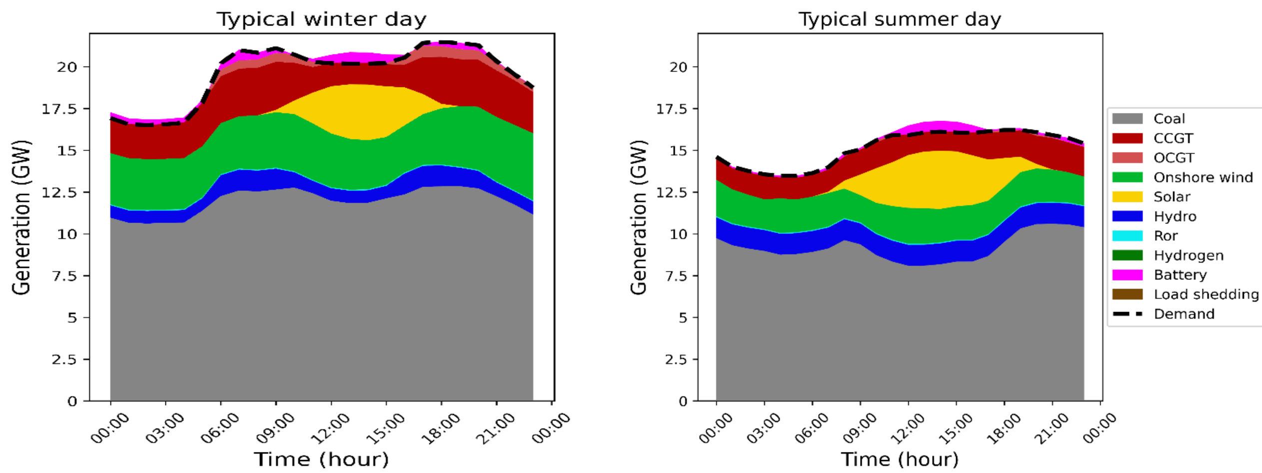
Figure 3 presents the generation profiles for a typical winter (a) and summer (b) day in Scenario 1, which assumes the integration of renewable energy sources for Kazakhstan's energy balance. In this scenario, a notable shift is observed with a 30% share of renewable energy sources (RES) in Kazakhstan's energy mix. The integration of RES, including wind, hydro, and solar energy, reflects a commitment to reducing greenhouse gas emissions and mitigating the impacts of climate change. This figure highlights a substantial increase in the utilization of renewable resources, indicating a significant transition towards sustainable energy practices.

4.3 Scenario 2: Coal exit

Scenario 2 involves a complete phase-out of coal-fired power, transitioning to a zero-emission landscape predominantly driven by renewable energy sources. After implementing the zero-emission expansion scenario, coal, which previously played a significant role, has now yielded its volume to wind power. Wind power emerges as the primary substitute for coal, symbolizing a substantial shift towards cleaner and more sustainable energy generation practices (Fig. 4).

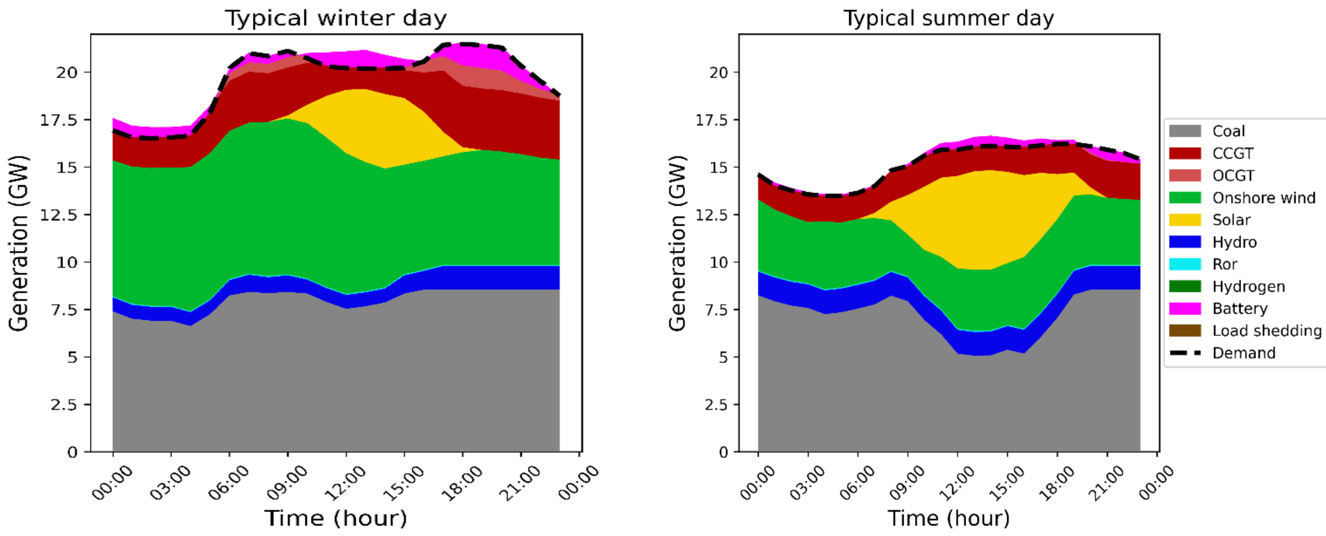
4.4 Scenario 3: New line with RES 30%

In Scenario 3 when adding a new line in the energy landscape of Kazakhstan that originates from the city of Atyrau to the city of Aktobe Fig. 5, the same additional 30% RES as in Scenario 1. Note that these western administration regions are mostly dependent on coal energy but because of their landscape can become weight generators with wind and solar energy. Significantly increases the weight of wind power stations compared to the base case Fig. 2. where no changes to the current state are added. It represents a shift towards sustainable development in these traditionally coal-dependent regions. This strategic move not only transforms the energy landscape, but also raises the profile of wind power plants,



(a) (b)

Fig. 3 Generation profiles for typical (a) winter and (b) summer day of the Scenario 1: RES share of 30% in 2035.



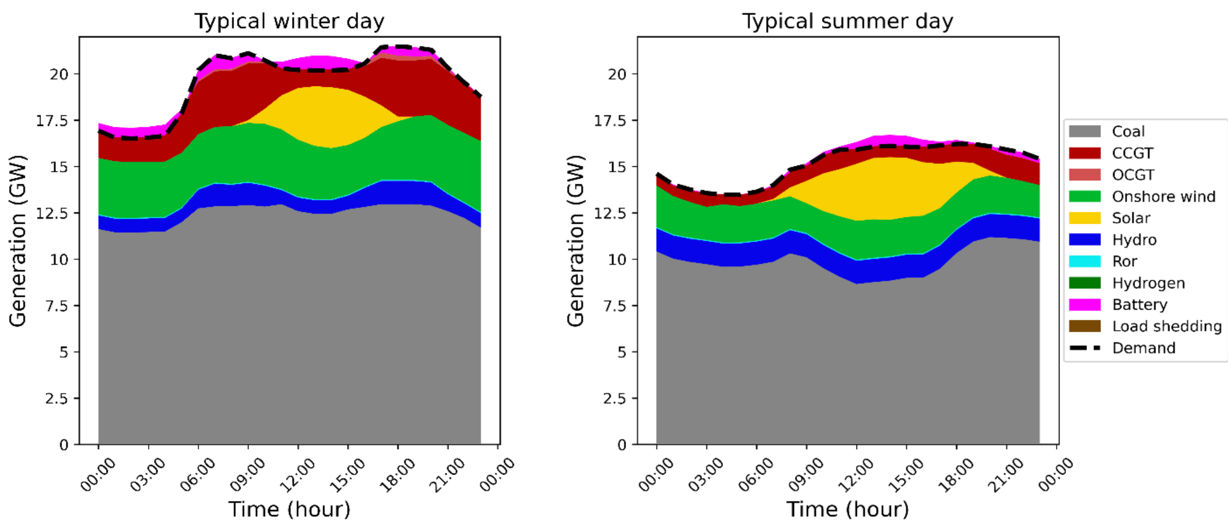
(a) (b)

Fig. 4 Generation profiles for typical (a) winter and (b) summer day of the Scenario 2: coal exit in 2035.

demonstrating a promising leap forward from the baseline.

5. Results and discussion

As mentioned above, 3 predictive scenarios for 2035 have been developed. Table 7 describes these scenarios. For 2020, the annual energy demand for the baseline scenario is equal to the real 107.34 TWh, while for 2035 152.40 TWh were taken. The capacity column describes the number of GW generated by coal, combined cycle power plants, open cycle gas turbines, hydropower, wind and solar. In the baseline scenario, the capacities are almost the same as the real values, in the scenarios for 2035, the amount of power generated by wind and solar increased in all scenarios, especially in scenario 2, since the amount of coal use in it has significantly decreased. The table also describes the amount of capacity that batteries can store in MWh in the future. The following is a description of the amount of generation in all scenarios, in it the same amount of coal is less in the second scenario, because of which the amount of generation with the help of the sun and wind is increased. Greenhouse gas emissions were not in the sources, but they could be calculated from other indicators. The line utilization column shows the highest number in 3 scenarios: 30.88%. In addition, separate columns also show the amount of generation of wind and solar energy by percentage and by GW in all scenarios, all generation using renewable energy sources. And finally, the total annual costs in billions of euros, with the highest figure in the second scenario "coal exit".



(a) (b)

Fig. 5 Generation profiles for typical (a) winter and (b) summer day of the Scenario 3: new line with RES 30% in 2035.

Table 7. Optimization results of PyPSA for the base and future scenarios.

			Scenario 0	Scenario 1	Scenario 2	Scenario3
		National report[4]	Base	RSE 30%	Coal exit	RSE 30%+New Lines
Year		2020	2020	2035	2035	2035
Annual Demand (TWh)		107.34	107.34	152.40	152.40	152.40
Capacity (GW)	Coal	13.41	12.97	12.97	8.54	12.97
	CCGT	4.00	3.48	3.48	3.48	3.48
	OCGT	2.02	1.63	1.63	1.63	1.63
	Hydro	2.73	2.73	2.73	2.73	2.73
	Wind	0.51	0.65	8.89	21.16	8.92
	Solar	0.96	0.82	7.38	11.72	7.20
	Total	23.62	22.27	37.06	49.26	36.92
Capacity (MWh)	H_2	-	0.00	7.34	39.28	6.28
	Batter	-	0.00	4829.77	5637.14	4644.77
Generation (GWh)	Coal	74497.6	74573.0	89065.3	50525.7	92673.5
	Gas	21692.7	20359.0	18260.3	18589.4	14694.3
	Hydro	9545.8	10862.9	10862.9	10857.5	10862.3
	Wind	1092.7	1718.0	25430.1	58264.1	25647.2
	Solar	1225.1	1048.5	9955.8	15189.0	9737.2
	Total	108080.9	108561.3	153573.7	153425.7	153614.7
Emission ($MtCo_2$)	Coal	-	25.35	30.28	17.18	31.51
	Gas	-	4.07	3.65	3.72	2.94
Line utilization (%)		-	26.77	29.21	26.71	30.88
Wind + Solar Generation	GWh	-	2.77	35.22	73.27	35.22
	%	-	2.55	22.93	47.70	22.93
All RES Generation	GWh	-	13.63	46.09	84.13	46.09
	%	-	12.55	30.00	54.77	30.00
Total Annual Cost (Billion Euros)		-	2.932	5.189	10.136	5.080

In Fig. 6, scenario 1 is visually shown on the map, in which the optimal RES capacities and line loading are located. The information provided in the results can be useful for energy and investment planning, for example, it is clearly visible on the map that in the future generation using solar energy will be particularly relevant in the south of the country, especially in Turkestan (2772 MW) and Almaty regions (2668MW), in the West – Aktobe with 2452 MW. In other areas, the generation of solar energy on the map does not reach 200 MW, for example, in Akmola region it is 100 MW, in Karaganda 190 MW, in Zhambyl 102 MW, in Kyzylorda 78 MW, in East Kazakhstan 30 MW, in other areas 0 generation. Wind farms can be located throughout Kazakhstan, especially in the central part with its 1,596 MW potential, in east Kazakhstan in the form of 832 MW and in the southern zones in Kyzylorda and Zhambyl regions at 833 MW and 542 MW respectively.

Summarizing all of the above, we can do a small SWOT analysis. The strengths of the PyPSA-KZ model include comprehensive data integration, open-source code and reproducibility of the model. The data were collected from various reports, sources, include annual electricity demand, power plant data, transmission line capacity, energy import and export data, which can provide a more accurate representation of the energy system, reliability and representativeness. And due to its open-source code, the model can be reproduced by different people, researchers, thanks to which it can be refined faster and more efficiently in the future. The weaknesses include its limited historical validation, because the model is based on forecast data for one year. Policy and investment planning can be attributed to the opportunities of this model, but in the case of constant updating of data, keeping them up to date. PyPSA-KZ has the potential to become a valuable tool for investment planning and scenario modeling, as the possibility of studying various scenarios, such as the integration of renewable energy sources or the abandonment of coal, can form the basis of policy decisions in the field of sustainable energy for the future. And finally, threats include dependence on external factors (political, global trends, unforeseen events), which in turn affects the long-term forecasts of the model. In envisioning the

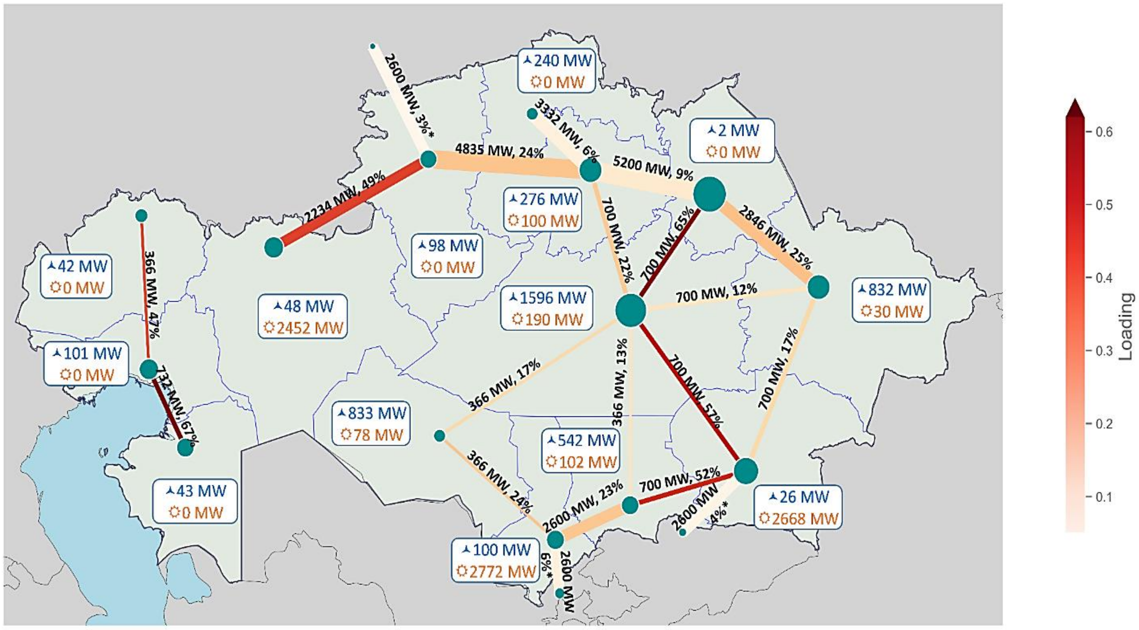


Fig. 6 Optimal RES capacities and line utilization for Scenario 1: RES share of 30% in 2035.

future of Kazakhstan's energy landscape and drawing insights from diverse domains on applying machine learning techniques[33] on spatial and long-term temporal data[34] we look ahead for the integration of data-driven algorithms and modelling future energy scenarios to guide Kazakhstan's transition towards sustainable energy.

6. Conclusion

This research paper provides a case study of the optimization of the energy sector of Kazakhstan with a focus on the integration of renewable energy sources, as well as in different scenarios the abandonment of coal in the near future. It is worth noting that the paper examines the differences between the administrative regions of Kazakhstan and how their landscape affects the distribution and integration of renewable energy sources (RES). Total, the results of three investment scenarios were presented: 1) renewable energy sources only, 2) renewable energy sources with linear investments and 3) renewable energy sources with accumulation and linear investments. In conclusion, the results of the scenario analysis not only deepen the understanding of energy system optimization, but also provide stakeholders with reliable information for the transition to sustainable energy solutions.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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