ASSESSMENT OF ELECTRICITY STORAGE OPTIONS FOR INTEGRATING RENEWABLE ENERGY IN RURAL KAZAKHSTAN

Vladislav Zavadskiy[1], Gita Revalde[2]
[1]UNEP CCC TNA Kazakhstan National Energy Expert, Denmark;
[2]Riga Technical University, Latvia
vladislav.zavadskiy@gmail.com, gita.revalde@rtu.lv

Abstract. Kazakhstan set the goal of being carbon neutral till 2060 and such ambitious targets required significant increase in renewable energy generation. Due to the nature of the renewable generation, it is critical to introduce electricity storage systems into the electrical grid. Nowadays there are different types of such solutions such as battery energy storage systems, cryogenic storage systems, hydroaccumulation power plants and many others. Our research is dedicated to the analysis of main modern electricity storage technologies and their possibilities of using in rural regions of Kazakhstan. Modelling part includes simulation of electricity generation from renewables in Kyzylorda region and introducing electrical storage facilities into the grid to support rural population. Kyzylorda region was chosen as the most sensitive in terms of water deficit region and and rather difficult conditions for farming. The economic efficiency of different storage options is discussed, emphasizing that cost-effectiveness remains a key factor in technology selection and policy decision-making. Discussion section represents the economic effectiveness of the storage systems where thermal storage systems represent the lowest LCOS value – 0.04 USD·kWh^{-1} and hydrogen fuel cells the highest – 0.830 USD·kWh^{-1}. But technical features and applicability factors cannot be ignored. As conclusions we provide policy-oriented recommendations and identify key success factors of introducing optimal electricity storage facilities.

Keywords: SDG, zero carbon, storage systems, BESS, cryogenic storage, rural regions, Kazakhstan.

1. Introduction

In February 2023, Kazakhstan approved its Strategy for Achieving Carbon Neutrality by 2060, which includes the development of green energy sources such as solar and wind power [1]. A characteristic feature of these energy sources is their variable nature (Fig. 1, 2) [2-4], which is an obstacle to their widespread implementation.

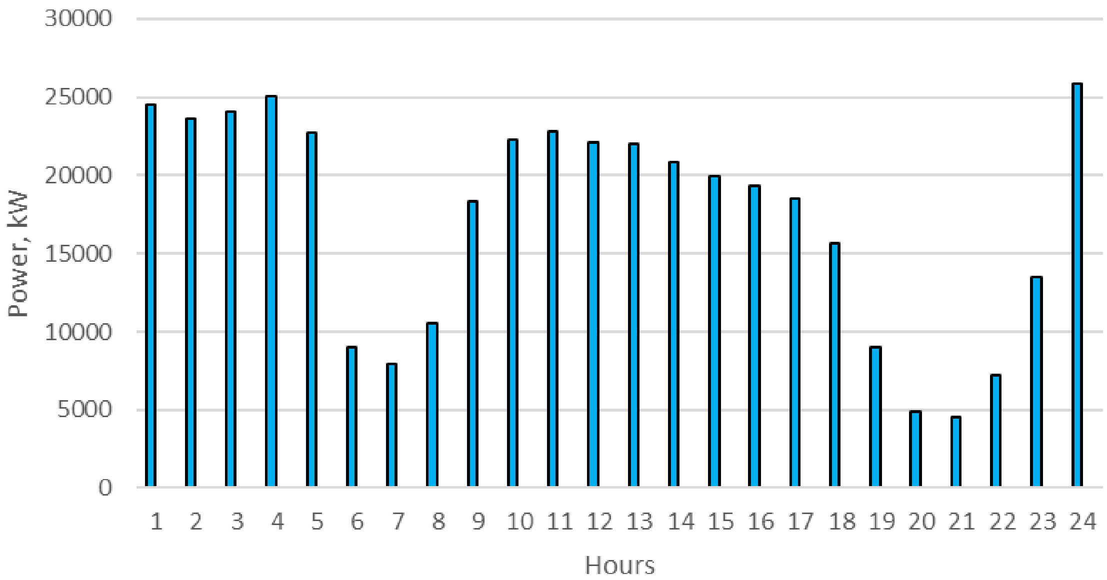

Fig. 1. **Renewables.ninja 100 MW wind farm power output profile simulation on 22.06.2019, Kyzylorda region [2-4]**

One of the promising solutions to this problem, along with strengthening intersystem connections, is the widespread introduction of energy storage systems. The purpose of these systems is to maintain the power output profile in accordance with the demand for electricity, adhering to the Unit commitment principle [2].

The most rapid growth technology is BESS (Battery Energy Storage System) – a technology that stores electrical energy in rechargeable batteries, such as lithium-ion batteries, and releases it as needed to provide a stable and uninterrupted power supply, especially when combined with renewable energy sources. Lithium-ion batteries have become widely used due to their advantages such as fast charge-discharge cycles, well-established production cycles, and accumulated operating experience [5].

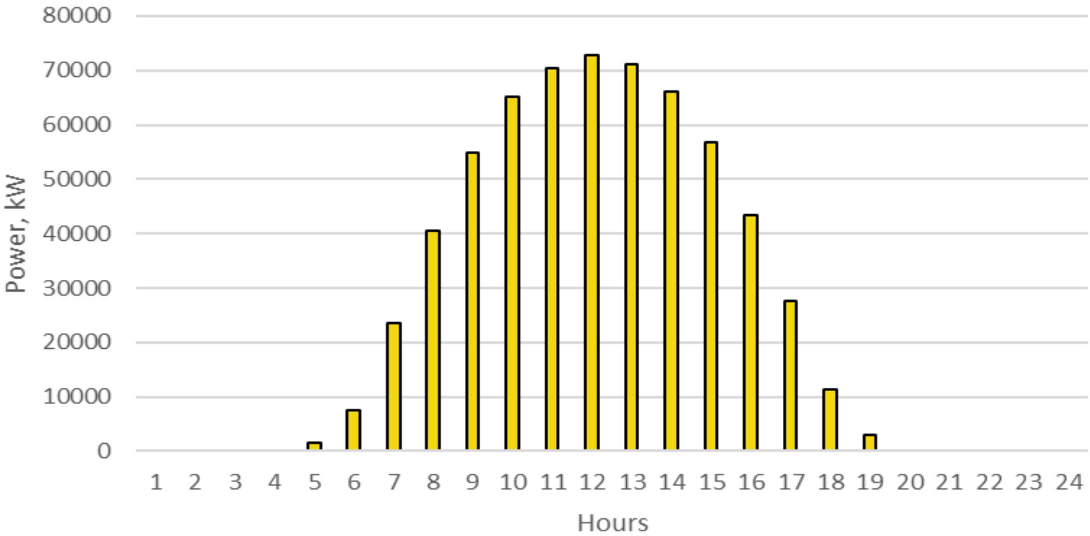

Fig. 2. **Renewables.ninja 100 MW PV solar plant power output profile simulation on 22.06.2019, Kyzylorda region [2-4]**

Systems based on the cryogenic principle of energy storage, by cooling gases or liquids, also offer advantages in terms of scalability, moderate cost, and relatively low environmental impact. Disadvantages include a relatively slow response to fluctuations in the power grid [6]. Energy storage systems can also be based on the transformation of electrical energy into thermal energy, using materials such as salt or sand as a heat transfer medium [7]. Traditionally, pumped storage hydroelectric power systems are a proven solution, however, they require a certain terrain, access to hydro resources and have average response parameters. Significant capital costs can also be attributed to the disadvantages of these systems [8]. Green hydrogen is also a promising technology for energy storage systems, but to date there are only pilot projects for its implementation, particularly in the Central Asian region [9].

Our research is unique for the region as for the first time we are analysing different types of the energy storage systems for Kazakhstan's southern arears, including thermal storage units.

2. Materials and methods

2.1. Evaluation of economic parameters for the implementation of energy storage systems

The cost of energy storage is a critical aspect to consider when assessing the feasibility and scalability of renewable energy systems. With continued improvements and cost reductions, energy storage can play a key role in ensuring a sustainable energy future.

The main method of calculating the cost of electricity storage is the calculation of the Levelized Cost of Storage (LCOS), which expresses the total cost for the entire life of the storage system (installation, operation and maintenance, replacement) in the form of the cost per kilowatt-hour (kWh) of electricity consumed over the entire service life. The key factors in calculating LCOS are the initial investment cost of the system, the cost of its operation and maintenance, the cost of energy to charge it, the efficiency of the circular cycle, and the total amount of energy released by the system over its lifetime [10].

The standard Levelized Cost of Storage (LCOS) formula is represented below [11]:

$$S = \frac{\sum_{t=1}^{N} \frac{CAPEX_t + O\,\&\,M_t + CC_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{ED_t}{(1+r)^t}}, \tag{1}$$

where $CAPEX_t$ – total capital expenditures in the period t;
CC – charging cost;
ED – energy discharged;
$O\&M_t$ – fixed operation and maintenance costs in the period t;
$(1 + r)^t$ – discount factor for the period t.

To calculate LCOS, the following simplified formula is used [11]:

$$LCOS \approx \frac{CRF \cdot CAPEX + FixedO\&M_t}{AED} , \tag{2}$$

where $CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$;
n – system lifetime (years);
$(1 + r)^n$ – discount factor for the period n;
AED – annual energy discharged.

Total capital expenditures are the largest part for the energy storage project, including the storage system itself, power conversion systems, battery management systems, energy management systems, civil engineering, installation and commissioning costs, and the necessary supporting infrastructure [11].

Operation and maintenance costs are also a significant cost item that tends to decrease as technology advances and is often a determining factor when choosing the type of the energy storage system.

To reduce energy losses, it is important to improve the charge-discharge efficiency. According to the estimations, by improving the charge-discharge efficiency parameter just by 5% the cost of kWh could be reduced by 8-10% [11].

LCOS is the main indicator for evaluating the economic efficiency of energy storage systems, and its calculation includes many factors that can influence the choice of the type of the electricity storage system.

2.2. Kyzylorda region rural arears renewable energy potential output modeling

For solar energy potential the Global Solar Atlas was used. The Global Solar Atlas uses three main different models [12]:

1. Solar radiation model;
2. Air temperature model;
3. PV power simulation model.

Simulations of solar radiation and air temperature lead to the creation of a series of pre-calculated data layers that can be obtained from (almost) any point on the map. The terrain and weather conditions are taken into account. Kyzylorda region is selected for the modelling as the whole area.

For each selected area, a multi-year sub-hourly time series of data from Solargis on solar radiation and air temperature is used as input data for calculations of photovoltaic energy production [12].

For wind energy potential the Global Wind Atlas was used. Kyzylorda region is selected for the modelling as the whole area. The process of modelling includes calculating of the local wind conditions for every 250 m at five altitudes: 10 m, 50 m, 100 m, 150 m and 200 m. Wind modelling contains flow models for orography, roughness and roughness change effects, displacement height and obstacle effects [13].

3. Results and discussion

Specific photovoltaic power output according to the Global Solar Atlas simulation for Kyzylorda region is equal to 4.6 kWh [12] as average (Fig. 3,4). This value is quite high compared to other regions of Kazakhstan, which allows us to confidently speak about the high potential for solar energy in this region.

By simulation using the Global Wind Atlas for Kyzylorda region, we got the result of the mean power density equal 616 $W \cdot m^{-2}$ (Fig. 5, 6) [13].

This value also allows us to speak about a fairly high wind energy potential in the region.

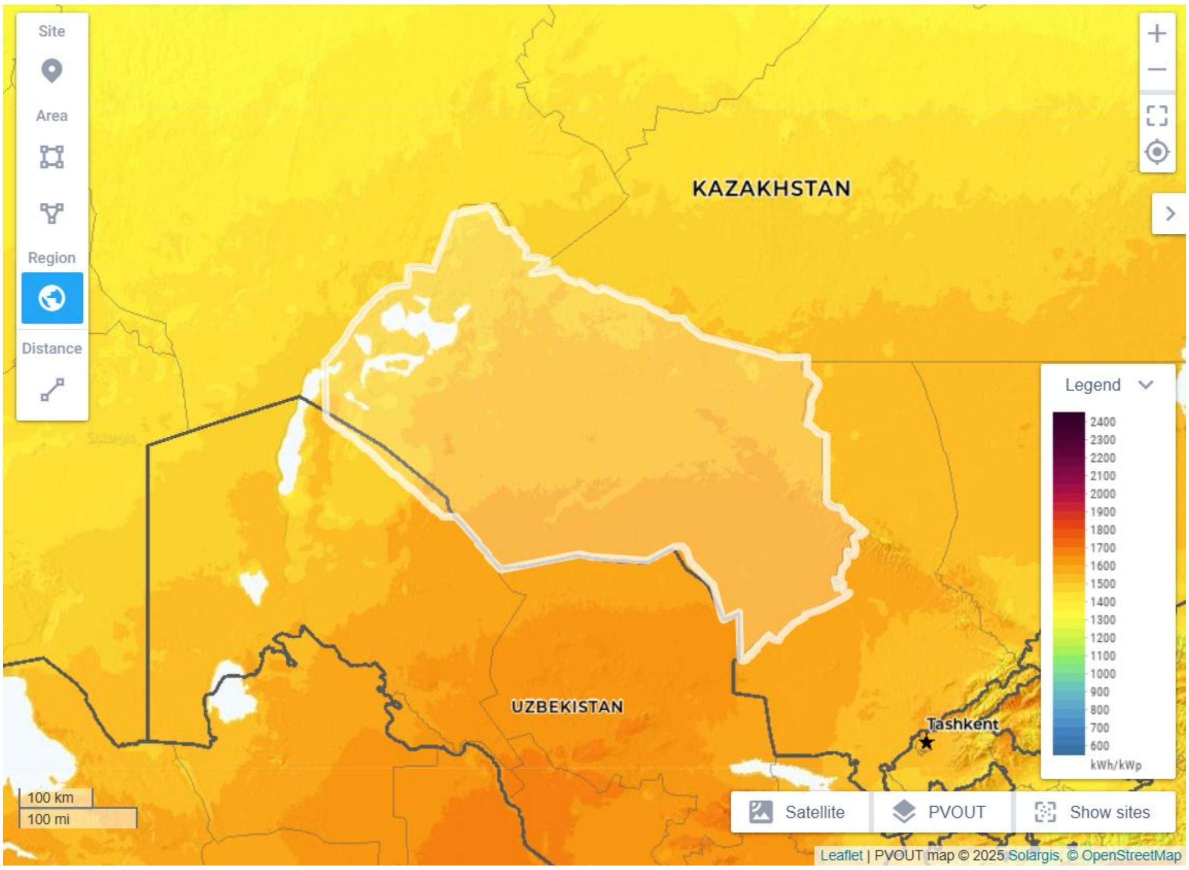

Fig. 3. **Specific photovoltaic power output, Kyzylorda region [12]**

Fig. 4. **Specific photovoltaic power output, Kyzylorda region [12]**

Thus, the obtained simulation data allows us to speak about the significant potential for solar and wind energy in the region and there are significant prospects for its implementation. However, as already mentioned, this requires the implementation of energy storage systems to maintain the required power output profile.

Therefore, the Levelized Cost of Storage (*LCOS*) analysis was conducted to evaluate the economic efficiency of the application and selection of the type of the energy storage system.

For the analysis and calculations, the following assumptions are applied for all types of the storage systems: discount rate (*r*) 8%; lifetime (*n*) 20 years; cycles per year – 300; *CRF*, according to formula 2 – 0.1019. Calculations are done for the storage duration of 3, 4, 5, 6, 7, 8 hours.

We normalize results per 1 kW system, so:

$$ED = t \cdot 1\text{kW} \cdot \eta\,, \tag{3}$$

where ED – energy discharged;
t – duration, h;
η – efficiency.

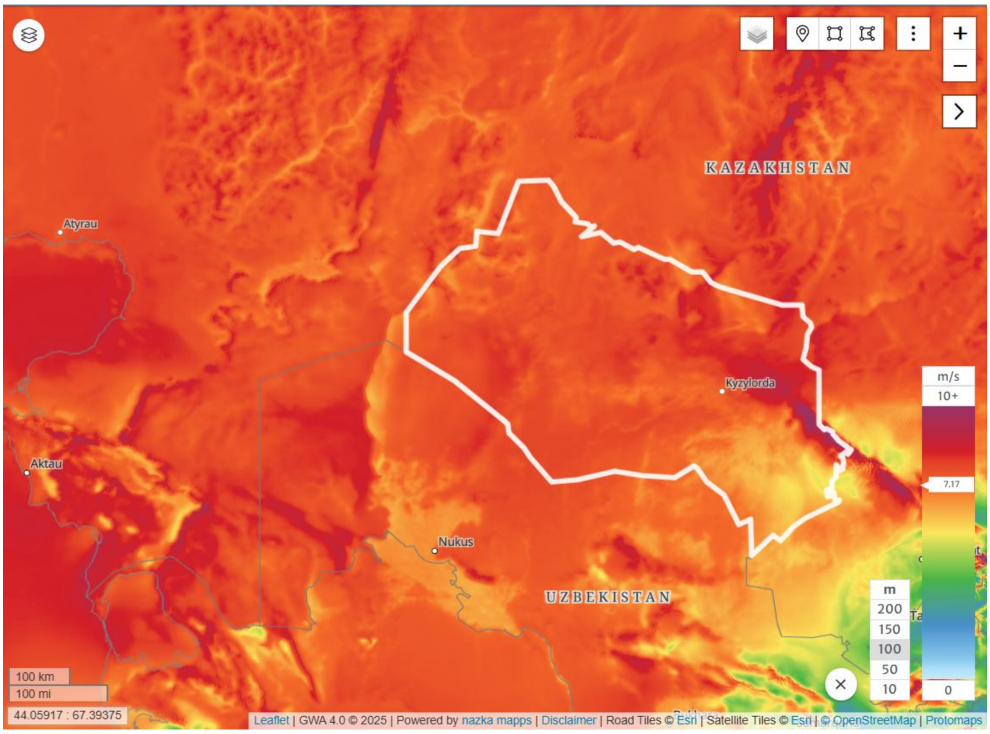

Fig. 5. **Mean wind power density at 100 m heights, Kyzylorda region [13]**

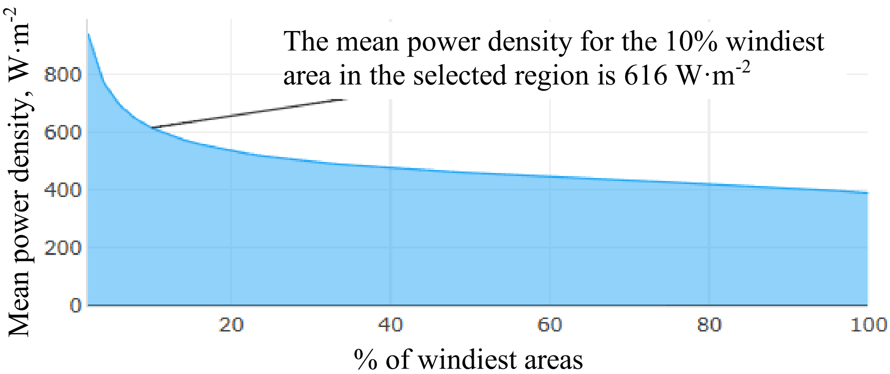

Fig. 6. **Mean wind power density at 100 m heights, Kyzylorda region [13]**

Initial data for the calculations and assumptions is represented in Table 1 [15-18].

Table 1

Energy storage systems unified assumptions

Parameter	Li-ion Battery	Compressed Air Energy Storage (CAES)	Hydrogen Fuel Cell Storage	Thermal Energy Storage
CAPEX (USD·kWh^{-1})	400	150	700	50
Fixed O&M (% of CAPEX·yr^{-1})	2%	3%	4%	2%
Efficiency	0.9	0.6	0.4	0.5

Lifetime, *n* (years)	20	20	20	20
Discount Rate, *r*	8%	8%	8%	8%
Cycles per year	300	300	300	300
CFR	0.1019	0.1019	0.1019	0.1019

Final LCOS Results Comparison is represented in Table 2.

Table 2

LCOS calculation Results Comparison (USD·kWh^{-1})

Duration (hours)	Li-ion Battery	Compressed Air Energy Storage (CAES)	Hydrogen Fuel Cell Storage	Thermal Energy Storage
3	0.181	0.110	0.830	0.041
4	0.176	0.108	0.810	0.040
5	0.173	0.107	0.800	0.039
6	0.171	0.106	0.790	0.039
7	0.170	0.106	0.780	0.038
8	0.169	0.105	0.780	0.038

According to the LCOS analysis and calculations, it turns out that the Li-ion batteries could be good for short-duration with high efficiency; CAES systems are competitive for medium and long duration; hydrogen cells are still expensive and the thermal energy storage systems have the lowest cost but limited to heat or indirect power use (Fig. 7).

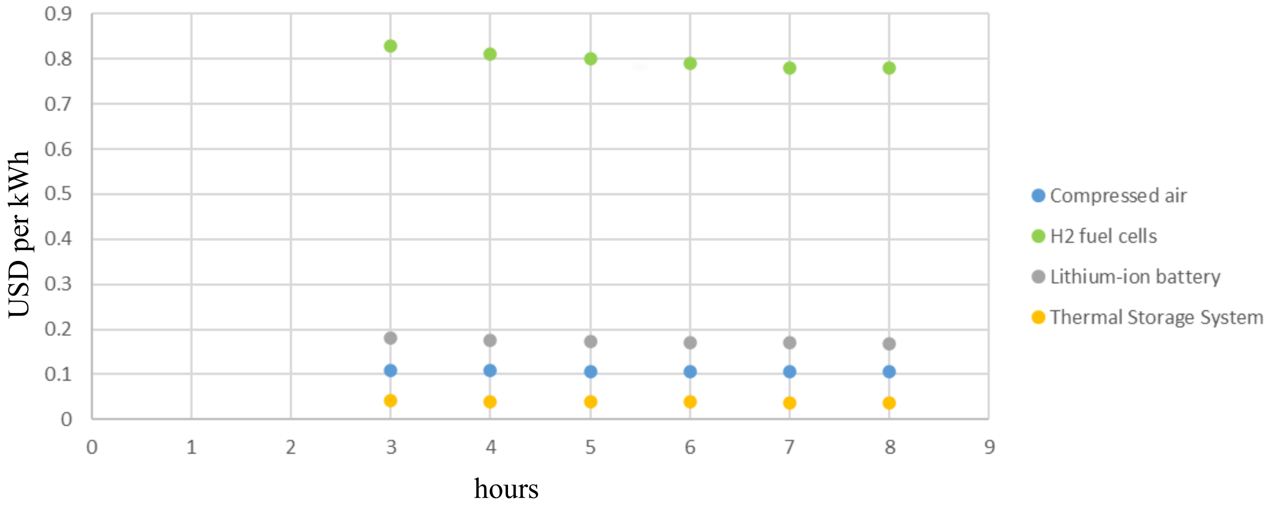

Fig. 7. **1 kW energy storage systems LCOS analysis**

Statistically, currently Li-ion batteries hold about 95% of the global market [19] being considered as a proof and reliable solution but other types are developing as well. However, when making the final decision on the type of the energy storage system to use, it is necessary to take into account not only the economic factors, but also the grid and system oprator requirements.

Conclusions

Currently, achieving the Sustainable Development Goals (SDG) is a critical task for humanity and participation of all countries is essential. Kazakhstan is the largest country in Central Asia and reaching SDG without any doubts will bring a positive impact for the country and the whole region.

Large-scale deployment of renewable energy sources will certainly contribute to achieving the stated goals, but it is limited by the very nature of these sources, namely their variable and unpredictable power output profile.

System operators sometimes lack the technical capacity to dispatch large amounts of renewable energy capacity, but the implementation of energy storage systems can solve this problem.

In our study, we selected rural areas of the Kyzylorda region of Kazakhstan, as a region with a risk of both water and electricity shortages. Supporting rural residents and women in this region is undoubtedly a priority. Improving access to affordable electricity and stability of supply will contribute to this goal.

The analysis showed the region's significant potential for wind and solar energy. Specific photovoltaic power output is equal to 4.6 kWh as average and the mean wind power density equals 616 $W \cdot m^{-2}$.

The Levelized Cost of Storage (LCOS) analysis brought to result in the thermal energy storage systems as the cheapest ones but limited to the heat usage. The Compressed Air Energy Storage (CAES) seems to be the compromised option.

Accordingly, taking into account the technical advantages of BESS and the price-falling trend they could be recommended as well. Considering the desert areas of the Kyzylorda region, sand thermal systems could be introduced as a long cycle storage system. Possible local manufacturing of such systems could significantly reduce the costs.

This topic requires government support, support from multilateral institutions, as well as the development of regulatory documentation on energy storage systems to ensure their broader support.

Thus, the conducted analysis showed the possibility of using various energy storage systems in the region, as a part of mitigation strategy, which will undoubtedly contribute to the implementation of plans for Kazakhstan to achieve carbon neutrality by 2060.

Author contributions

Both authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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