Transition towards 100% renewable power and heat supply for energy intensive economies and severe continental climate conditions: Case for Kazakhstan

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ABSTRACT

Transition towards 100% renewable energy supply is a challenging aim for many regions in the world. Even in regions with excellent availability of wind and solar resources, such factors as limited availability of flexible renewable energy resources, low flexibility of demand, and high seasonality of energy supply and demand can impede the transition. All these factors can be found for the case of Kazakhstan, a mostly steppe country with harsh continental climate conditions and an energy intensive economy dominated by fossil fuels. Results of the simulation using the LUT Energy System Transition modelling tool show that even under these conditions, the power and heat supply system of Kazakhstan can transition towards 100% renewable energy by 2050. A renewable-based electricity only system will be lower in cost than the existing fossil-based system, with levelised cost of electricity of 54 €/MWh in 2050. The heat system transition requires installation of substantial storage capacities to compensate for seasonal heat demand variations. Electrical heating will become the main source of heat for both district and individual heating sectors with heat cost of about 45 €/MWh and electricity cost of around 56 €/MWh for integrated sectors in 2050. According to these results, transition towards a 100% renewable power and heat supply system is technically feasible and economically viable even in countries with harsh climatic conditions.

HIGHLIGHTS

- 100% RE can supply an energy intensive economy under harsh climate conditions
- Substantial storage capacities are needed to compensate seasonality of heat demand
- Electrical heating becomes the main source of heat
- 100% RE can provide energy at a cost of 45 €/MWh for heat and 56 €/MWh for power

KEYWORDS

100% Renewable Energy, energy transition, energy system optimization, power sector, heat sector, sector coupling.

NOMENCLATURE

A-CAES	adiabatic compressed air energy storage
CAGR	compound annual growth rate
Capex	capital expenditures
CF	capacity factor
CHP	combined heat and power
CCGT	combined cycle gas turbines
CSP	concentrating solar power
DAC	CO_2 direct air capture
FLh	full load hours
GHG	greenhouse gases
HVAC	high voltage alternating current
HVDC	high voltage direct current
ICE	internal combustion engine
Opex	Operational expenditures
OCGT	open cycle gas turbines
PHES	pumped hydro energy storage
PtG	power-to-gas
PV	photovoltaic
RE	renewable energy
SNG	synthetic natural gas
TES	thermal energy storage
WACC	weighted average cost of capital

1. INTRODUCTION

Located in the heart of Eurasia, Kazakhstan is an excellent representative of the entire Eurasian region with energy intensive industries, an energy sector based economy, low population density, aging energy infrastructure and excellent availability of renewable energy (RE) resources. Eurasia is one of the major energy exporting regions in the world, with significant oil, gas and coal reserves and a large export market share. Most of the energy system infrastructure was inherited from the Soviet era and needs to be modernised in the decades to come. Existing power and heat generation capacities use locally available fossil resources and the share of modern renewables in the total mix is very small. In Kazakhstan, most of the electricity and heat are generated from coal. Kazakhstan is a country richly endowed with fossil fuels resources, such as coal, oil, gas and uranium [1]. Rapid economic growth in the past decades was mostly supported by growth of the fossil fuel based energy sector [2,3] leading to fast growth of emissions. Between 1999 and 2014, CO_2 emissions of Kazakhstan increased from 111 Mt_{CO2} to 260 Mt_{CO2} [3]. The CO_2 emissions per capita in the country were 1.3 times higher than the average value of OECD countries [4]. However, aging existing infrastructure and the need to modernise the energy sector [5] presents a great opportunity for the whole region to build a new, sustainable and renewable based energy system. Kazakhstan could become the trailblazer for the entire Eurasia and similar regions, showing feasibility of RE systems under conditions of harsh continental climate, energy intensive economy. Energy transition towards higher shares of RE is on the agenda of the

Kazakh government since 2011 [6]. Since the last decade, the share of modern RE is growing fast and this growth will continue after the integration of RE auction mechanism in 2018. In total, Kazakhstan has a great potential to build a sustainable and RE-based system with excellent solar, wind, hydro and biomass potentials.

Perspectives of transitioning towards energy systems with higher shares of renewables and 100% RE based systems, the only fully sustainable way to build a zero emission system, attract attention in many regions of the world [7]. The transformation towards RE based systems should be technically feasible and economically viable [8]. From the technical point of view, technologies necessary for RE based system's operation, generation, storage and bridging are available [8]. Further, cost to of RE generation and power storage options proceed to decline due to the technical development [9] and industrial scaling. However, issues such as, inertia in systems without rotating masses of synchronous generators, or stability in isolated RE-based micro-grids raises doubt for a fully sustainable energy systems. But, synchronous generators' inertia can be substituted by integration of synthetic inertia, as shown for a 100% RE system in Sub-Saharan Africa [10], and by the use of optimisation of generation and storage power converters operation algorithms [11]. RE-based micro-grids stability can be significantly improved by an agile system control design, implementing load sharing strategies for distributed generators [12], enabling improved frequency control for islanded micro-grids [13] and optimisation of distributed storage utilisation [14].

Various studies show that available RE resources are sufficient to satisfy power demand in all regions in the world, including Kazakhstan [15]. Further, some studies show that RE resources can satisfy annual energy demand of the integrated energy system on global scale [16,17]. Studies on the structure of RE-based systems are presented for different regions on different levels. RE-based energy systems are discussed as the backbone of electricity supply systems of archipelagos [18], where each island currently represents an isolated energy system and centralised or decentralised supply options should be considered for the system development [19]. Possibilities to satisfy the electricity demand in the industrially developed country of Japan with RE sources is discussed in Esteban et al. [20]. Many articles describe the possible future RE systems modelled using EnergyPlan, an energy system simulation tool, results show the possibility to satisfy the energy demand for every hour of the year for the Ireland [21], Finland [22], Åland island [23], and whole South East Europe [24]. Another widely used tool, JRC-EU-TIMES also allows to automatically optimise the energy system structure, generation and storage capacity mix, for the year represented in a set of representative time slices. This tool was used in the Heat Roadmap Europe project and in numerous studies concerning European energy systems [25]. However, perspectives of energy system transition in countries with severe climatic conditions, including a high variation of seasons, and high daily and yearly temperature differences, is not widely discussed in the literature. The transition in these countries will be complicated due to additional flexibility and storage demand to compensate extra energy requirement in the winter time, when RE generation may be limited. Assembayeva et al. [26] discuss the perspectives of RE integration in the power sector of Kazakhstan and the impact of storage in such a system. This study shows that an energy system with a high share of RE in the power supply is feasible, however an option of a 100% RE system is not tested. The heat sector, for which energy demand is considerably high in countries with harsh climatic conditions, is not included in the study and its impact on the system is not discussed. At the same time, transition pathways from the current energy system structure towards the potential high RE systems are not discussed in the studies mentioned earlier, however an optimal transition pathway is an important concern, especially for the countries heavily dependent on aging fossil fuel based infrastructure.

Testing the feasibility of RE-based power and heat sectors for countries with harsh climatic conditions is most important due to the high variability in seasons, where power and heat requirements compared to a more stable industrial and transportation energy demands. Additionally, feasibility should be tested in full hourly resolution to guarantee the stability of the RE-based system and the proper estimation of the energy storage requirements considering the nexus between the RE share, storage requirements, and curtailment [27]. Feasibility of 100% RE systems in such worse case conditions can prove the feasibility of RE systems in general. Kazakhstan's energy system represents such a case and can be used as a model for such class of countries. At the same time, an energy intensive economy with an aging inflexible coal-based generation represents the worse case starting condition for an energy transition, since high shares of modern VRE have to be integrated on early stages of the transition when flexibility options are on high cost level. Transition modelling for these climates, energy demands, and existing system structure conditions will show most important challenges and provide valuable solutions for most complicated transformation cases.

This research suggests a transition pathway for Kazakhstan to reach an optimal and sustainable energy system by 2050. This pathway can be an example for countries with harsh climate conditions and energy intensive economies. Kazakhstan is a case country for all other countries of the Eurasian region, experiencing the same problems: aging of power capacities, high shares of inefficient fossil-based generation and high GHG emissions. Background information on the case country Kazakhstan is provided in the Supplementary Materials. Such a transition can result not only in lower GHG emissions and higher overall sustainability of the energy system, but also to higher energy efficiency due to better integration of energy sectors as it is discussed for Smart Energy Systems [28,29]. However, in this study we do not consider the transport sector and demand for non-energetic industrial feedstock. The optimisation model simulates a transition towards 100% RE power and heat supply systems for Kazakhstan by 2050, with consideration of the fast growing energy demand.

2. MATERIALS AND METHODS

Kazakhstan's power system was modelled with the LUT Energy System Transition modelling tool [30,15]. The LUT model simulates an energy system development under specific given conditions. For every time step the model defines a cost optimal energy system structure and operation mode for the given set of constraints: power demand, heat demand for industry, space and domestic water heating, available generation and storage technologies, financial and technical parameters, limits on installed capacity for all available technologies. The model is based on linear optimisation and performed on an hourly resolution for each year, which increases reliability of the results in comparison to time slices or annual energy balancing approaches. The target of the optimisation is minimisation of the total system cost. Costs of the system are calculated as the sum of the annual capital and operational expenditures (including ramping costs) for all available technologies. The transition simulation was performed for the period from 2015 to 2050 with 5-year time steps.

The distributed generation and self-consumption of residential, commercial and industrial prosumers are included in the energy system analysis and defined with a special model describing the development of the individual power and heat generation capacities. The prosumers can install their own rooftop PV systems, lithium ion batteries, buy power from the grid or sell surplus electricity in order to fulfil their demand, at the same time prosumers can install individual heaters for space and water heating. The target function for prosumers is minimisation of the cost of consumed electricity and heat, calculated as a sum of self-generation equipment annual cost, cost of fuels and cost of electricity consumed from the grid. The share of consumers who are expected to be interested in own generation gradually increases from 3% in 2015 to 15% in 2050, not reaching the in-built limit of 20%. The flow diagram of the LUT model from various input data to output results can be found in Figure 1. The Supplementary Material in the Appendix A provides the consistent description of the model and the full set of all technical and financial assumptions used in the modelling of the energy transition in Kazakhstan (Tables A1 and A2).

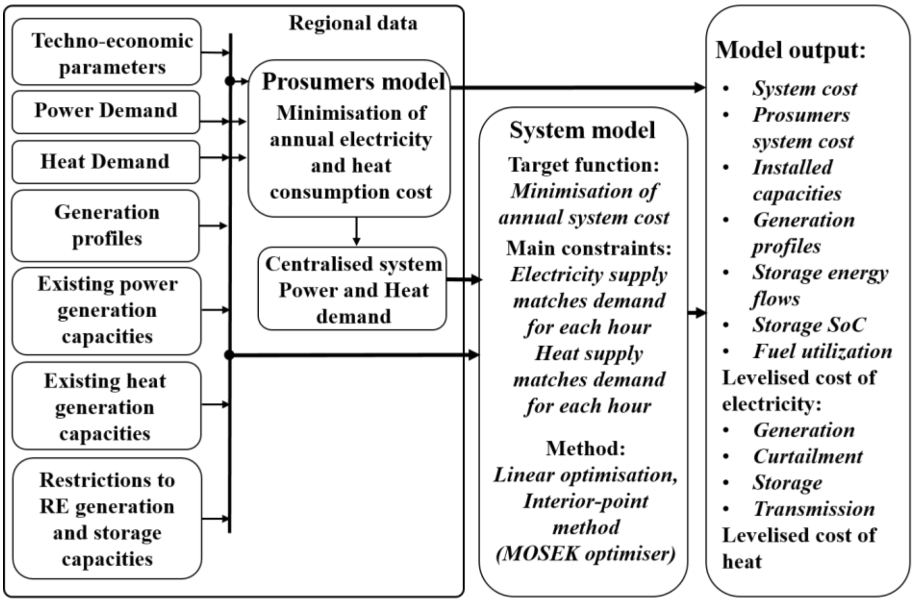

Figure 1. Main inputs and outputs of the LUT Energy System model

2.1. Applied technologies

The model has integrated all crucial aspects of an energy system. For Kazakhstan, technologies introduced to the model can be classified into five main categories:

- Electricity generation: fossil, nuclear and RE technologies
- Heat generation: fossil and RE technologies
- Energy storage
- Energy sector bridging
- Electricity transmission

Fossil electricity generation technologies are coal power plants, combined heat and power (CHP), oil based internal combustion engine (ICE) and CHP, open cycle (OCGT) and combined cycle gas turbines (CCGT), gas based CHP. RE electricity generation technologies are solar PV (optimally fixed-tilted, single-axis north-south tracking and rooftop), wind turbines, hydro power (run-of-river and reservoir), geothermal and bio energy (solid biomass, biogas and waste-to-energy power plants and CHP). Fossil heat generation technologies are coal-based district heating, oil-based district and individual scale boilers, gas-based district and individual scale boilers. RE heat generation technologies are concentrating solar power (CSP) parabolic fields, individual solar thermal water heaters, geothermal district heaters and bio energy (solid biomass, biogas district heat and individual boilers).

Storage technologies can be divided in 3 main categories: short-term storage – Li-ion batteries and pumped hydro energy storage (PHES); medium-term storage – adiabatic compressed air energy storage (A-CAES), high and medium temperature thermal energy storage (TES) technologies; long-term gas storage including power-to-gas (PtG) technology, which allows to produce synthetic methane for the system use.

Bridging technologies are power-to-gas, steam turbines, electrical heaters, district and individual scale heat pumps and direct electrical heaters. These technologies convert energy of one sector into valuable products for another sector in order to increase total system flexibility, efficiency and decrease overall costs.

The energy transition simulation takes into account the existing AC power grid of Kazakhstan, its development trends and projected overall electricity transmission and distribution losses [31].

Figure 2 presents the block diagram of the energy system model and all technologies available for the energy transition in Kazakhstan.

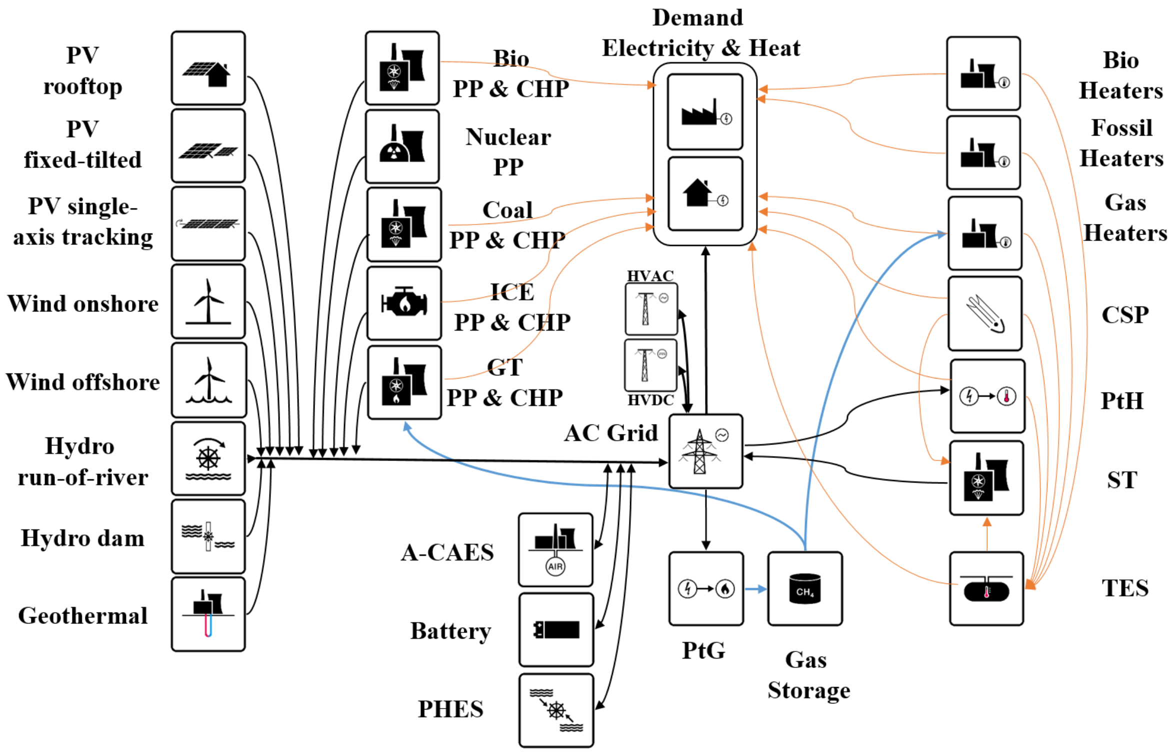

Figure 2. Block diagram of the LUT Energy System Transition model. This is composed of energy converters for power and heat, storage technologies, transmission options and demand sectors.

2.2. Applied scenarios

In this paper, two main scenarios were studied for the energy transition of Kazakhstan: power sector and integrated power and heat sector transition. These scenarios focus on achieving a 100% RE system by 2050, so no fossil coal, gas, oil or uranium can be used in the system in 2050. The power scenario focuses on the power sector – for every 5-year time step of the transition, the system has to satisfy the electricity and heat demand of residential, commercial and industrial sectors for every hour of a year. Power and heat integration scenario also takes into account industrial heat demand, space and domestic water heating.
Availability of RE is calculated using weather data from NASA [32,33], and German Aerospace Centre [34], the calculations method is described in the section 2.3 and respective

input and constraints are provided in the Appendix A (Tables A5-A6 and Figures A1, A2, A4).

The energy system transition modelling for Kazakhstan was designed with four important constraints:

- No new nuclear, coal or oil-based power plants or combined heat and power (CHP) plants could be installed after 2015
- No new coal or oil-based district heating boilers could be installed after 2015
- Run-of-river, reservoir (dam) hydropower plants and pumped hydro storage are refurbished every 35 years and never decommissioned, based on empiric observation [35].
- RE capacity shares cannot increase more than by 4% per year, 3% between 2015 and 2020, based on empiric observation [35].

Gas based power plants, CHP and boilers can be installed after 2015 due to lower GHG emissions and the possibility to accommodate synthetic natural gas (SNG) or bio-methane into the system [36].

2.3. Financial and technical assumptions

The financial and technical assumptions are mostly taken from the European Commission [8], but also from other sources [37-50]. The financial and technical assumptions for all power and heat generation capacities, storage, transmission and bringing technologies and fuels with respective references are presented in the Appendix A (Table A1 and A2). Assumptions are made in 5-year time steps from the year 2015 to 2050. For all scenarios, weighted average cost of capital (WACC) is set to 7%, but for residential PV prosumers WACC is set to 4% due to lower financial return requirements. Electricity prices for residential, commercial and industrial consumers were derived according to [51], and extended to 2050, and can be found in the Appendix A (Table A3). Excess electricity generated by prosumers is fed into the national grid and is assumed to be sold for a transfer price of 0.02 €/kWh. The model ensures that prosumers satisfy their own demand for electricity before feeding it into the grid. District heating efficiency increases from the Eurasian region's average estimate of 85% to 92% in 2050 [52] and the district heating share in space and domestic water heating continuously decreases from 70% in 2015 [53, 54] to 50% in 2050.

2.4. Demand and resource potential for renewable technologies

Electricity demand assumptions are based on IEA data. Actual electricity consumption for year 2015 is taken from IEA statistics [53], and future consumption values are calculated based on annual growth rates for the Eurasian region from IEA WEO 2017 [55]. The annual electricity demand is converted into hourly profiles according to the method presented in Toktarova et al. [56]. Profiles for industrial heat demand, space and water heating demand are taken from Barbosa et al. [57]. Power and heat demand assumptions for each step of the transition are provided in the Appendix A (Table A4 and Figures A3).

The generation profiles for single-axis tracking, optimally fixed tilted PV, solar CSP and wind energy were calculated according to [30] using global weather data for the year 2005 from NASA [32,33] and German Aerospace Centre [34]. The hydropower feed-in profiles are computed based on the monthly resolved precipitation data for the year 2005 as a normalised sum of precipitation in the regions based on [58]. Hourly capacity factor profiles for single-axis tracking PV and wind turbines are presented in the Appendix A (Figure A5).The potentials for biomass and waste resources were taken from [59] and classified into four main categories: forestry industry wastes, solid wastes, solid residues and biogas. The costs for biomass are calculated using data from the IEA [60] and Intergovernmental Panel on Climate Change (IPCC) data [61]. For solid waste a 50 €/ton gate fee was assumed for 2015, rising to 100 €/ton in 2050. Geothermal energy potential was calculated according to the method described in [62]. FLh for wind turbines, solar PV and hydro plants, potentials of bio and geothermal energy are provided in the Appendix A (Table A5). The lower and upper limits of renewables and fossil fuels are provided in the Appendix A (Table A6). The A-CAES storage potential is based on a global A-CAES resource assessment [63].

3. RESULTS AND DISCUSSION

3.1. Transition scenario for the power sector

Possibility and strategy of the energy sector transition towards a 100% RE-based system in Kazakhstan and the whole Eurasian region is the main focus area of this research. Currently, energy system of the region mostly relies on fossil-based generation technologies, predominantly coal and gas in Kazakhstan. Most of these capacities were built more than 25 years ago (95% of all coal power plants were built before 1990) and have to be decommissioned very soon. These decommissioned capacities can be substituted by sustainable RE generation technologies. The results of the simulation show that the transition of the power sector is possible and a 100% RE system can be reached by 2050. Figure 3 presents the structure of the energy system for every 5-year time step for the transition period.

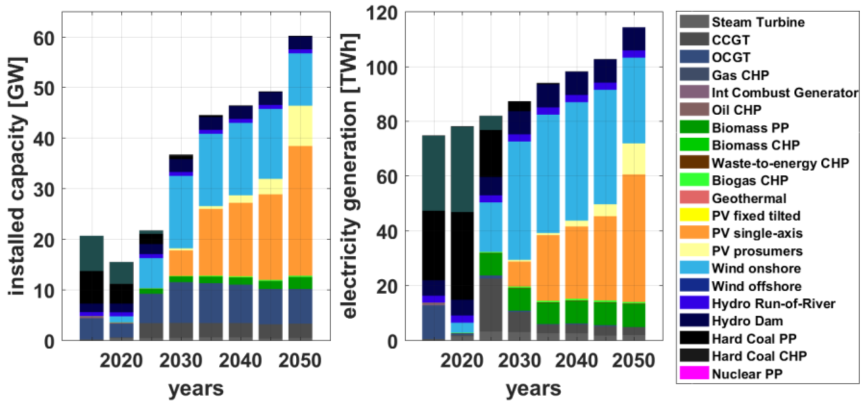

Figure 3. Installed capacities of different technologies (left) and power generation (right) for the power system transition scenario.

Figure 3 depicts that for the initial years of the transition, coal generation capacities are dominant in the system, but in 2020 to 2030 most of these old capacities are decommissioned due to aging and are substituted mostly by new wind and CCGT generation. This period shows the most significant change of the system structure – after 2025 RE represents more than half of the system capacity. In the following periods, the share of RE sources gradually increases. Significant capacities of wind generation are installed in 2025 and 2030, but in later periods, wind capacities stay the same and after 2045 they are partially substituted by single-axis tracking PV. After 2030, solar PV is the fastest growing technology in the system, in 2040 total PV capacity exceeds the capacities of all other technologies. By 2050, PV forms around 50% of the total system capacity, however, the share of fixed-tilted PV is not relevant, since 13% (about 8 GW) of the generation capacities are contributed by PV prosumers and 42% (more than 25 GW) are single-axis tracking PV power plants – the least cost energy source in the system. In total, solar PV contributes to more than 52% (about 58 TWh) of total electricity generation, wind energy to less than 30% (30 TWh) and hydropower to about 10%

(11 TWh). Biogas, biomass and waste incinerator power plant generation stays stable over the years on the level about 9 TWh, contributing to 7% of total electricity generation. Biomass utilisation is mostly limited by sustainably available resources of biomass. However, the capacities of biomass-based power plants gradually increase over time to increase the flexibility of the system and decrease the storage requirements. Gas turbine capacity stays constant after fast growth in 2025, gas based power generation gradually decreases – with increase of gas and CO_2 emission costs, gas generation becomes more expensive for the system. In 2050, fossil methane is banned in the system, gas turbines use only bio-methane and synthetic methane from Power-to-Gas (PtG). Due to relatively low electricity distribution prices, before 2030, prosumer PV is not installed, but later it becomes cost competitive for commercial and industrial prosumers.

As a consequence of the growth of the RE shares, one can observe a growing demand in storage capacities. Throughput of storage increases from zero in 2015 and 2 TWh in 2020 to 24.5 TWh in 2050, as it can be seen in Figure 4.

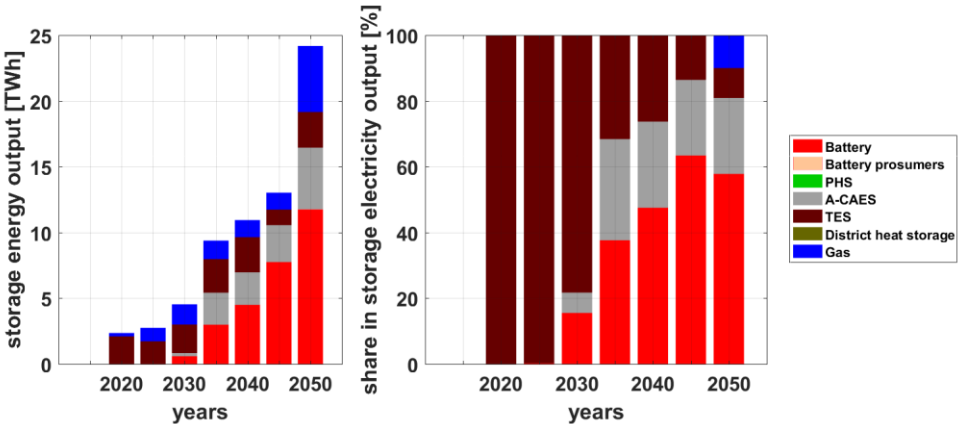

Figure 4. Storage output for the power system transition scenario.

For 2020, thermal energy storage is the only economically feasible solution, with the growth of RE shares in the system and cost decrease of storage technologies other types of storage appear. The most important role is played by short-term Li-ion battery storage, which is very important for systems with high PV generation shares [64]. Prosumer batteries never appear in the system because of the comparably low retail electricity prices, thus the expected electricity distribution price is too low for PV prosumers to invest in their own energy storage systems. Mid-term adiabatic compressed air energy storage also plays an important role in the system and generally complements wind generation, as also described in more detail by Gulagi et al. [65]. Gas storage appears in the system only during the last step of the transition, long-term SNG storage is needed to compensate seasonal demand fluctuations in the harsh climatic conditions of Kazakhstan. Gas storage installed capacity reaches 3 TWh in 2050, however the share in total electricity demand is limited to 10% of all stored electricity.

The power system transition results in a 100% RE system by 2050, and no electricity is generated with fossil fuel utilisation. Furthermore, the energy transition leads to lower costs of electricity generation compared to the current system, as it can be seen from Figure 5.

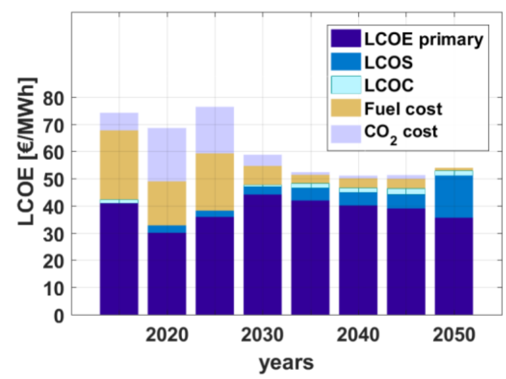

Figure 5. LCOE components for the power system transition scenario.

Figure 5 shows that levelised cost of electricity (LCOE) decreases from 74 €/MWh in 2015 to 54 €/MWh in 2050. For the first decade, the system is still based on fossil generation, thus the share of fuel and CO_2 emission costs in total LCOE is significant. With the integration of new RE capacities, the share of fuel costs decreases and capital costs become the main components of the LCOE. At the same time, some energy is curtailed due to inflexibility of RE sources. This effect leads to an increasing levelised cost of storage (LCOS) and levelised cost of curtailment (LCOC) components. The period of the year 2025 is different and breaks the trend of gradual decrease in LCOE, this is due to sharp decommissioning of aged coal generation capacities, which can be interpreted as a shock for the system. As a result, huge new capacities of RE and gas turbines need to be installed. As the resulting capital costs increase sharply, while fuel and CO_2 costs stay almost the same. Finally, one can see the very high LCOE for this decisive transition step. The last step of the transition also shows some challenges, due to seasonality of the continental climate of Eurasia. Power demand during winter significantly increases and long-term storage needs to be installed in order to compensate the demand and supply fluctuations. Power-to-Gas based gas storage significantly increases the cost of the system and results in slightly higher LCOE in comparison to 2045. If all capacities of the year 2050 were built for the financial and technical assumptions of the year 2050, then the total LCOE would be 16% lower at 44 €/MWh, a cost level which can be expected for the periods after 2050.

3.2. Transition scenarios for power and heat integrated system

Integration of different sectors can be very valuable for the system as it was seen for other regions [30,66], but at the same time it can provoke additional problems, such as resource limitations, mainly due to increased generation demand. Figure 6 presents the power system structure and generation for the power and heat integrated system scenario. Figure 7 presents the heat generation capacities structure and the heat generation for the power and heat integrated system scenario.

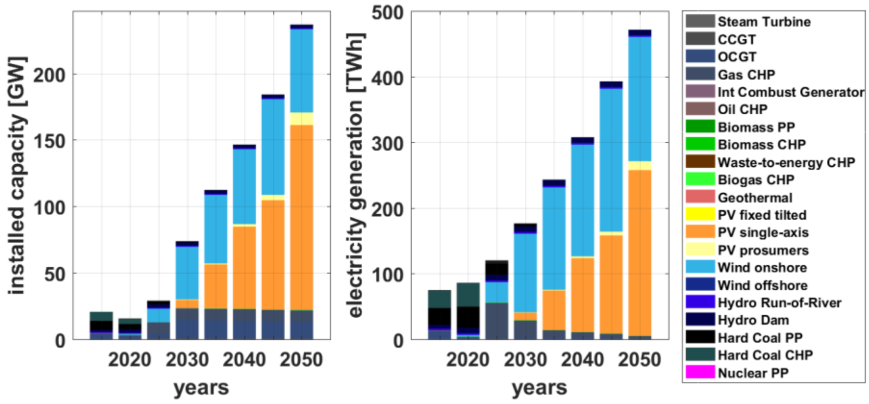

Figure 6. Installed capacities of different power generating technologies (left) and annual power generation (right).

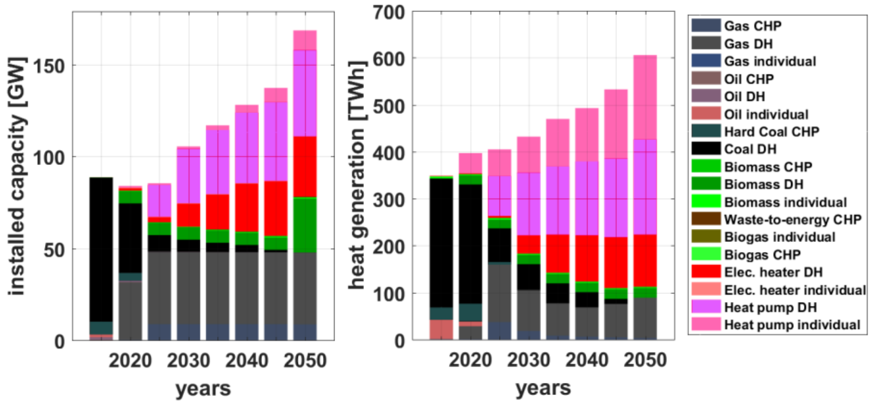

Figure 7. Installed capacities of different heat generating technologies (left) and annual heat generation (right).

The power sector structure of the integrated system is comparable to the one of the power only system, however power generation and capacities grow faster in order to satisfy rising demand from an electrified heat generation sector. The transition process follows the same pattern as in the case of the power only sector: wind capacities grow significantly during 2020 to 2030 and later stagnate, while solar PV consistently grows after 2030. Wind and solar are the main power sources starting from 2035, shares of other RE sources are limited by their maximum potential. In 2050, solar PV provides more than 50% (about 270 TWh) of the consumed electricity, the wind share is about 40% (about 165 TWh), which is higher than the case for power only scenario. Rest of electricity is generated by hydropower plants (about 11 TWh) and biomass plants (less than 1 TWh). The system chooses to install more wind turbines which are an expensive energy source in 2050, as the wind availability is more stable throughout the year and other resources such as hydropower and biomass reach their resource limits.

The heating sector of Kazakhstan transitions from the current, mostly dependent on coal-based district heating, to a mostly electricity-based heating system by 2050. During the transition, the system substitutes coal capacities first by gas and biomass sources and later by electrical heating, mainly through electric heat pumps and direct electric heaters. At the end of the transition, most of the heat is produced by heat pumps and gas, which is stored seasonally. While biomass heat is used mainly to satisfy high temperature heat demand of industry, additional electrical heaters provide medium temperature heat for industry. The individual heating shares gradually increases from 15% in 2015 to 25% in 2050. The individual heating sector is electrified much faster: in 2020, 78% of heat is produced by heat pumps; later this share steadily grows and reaches 99% in 2050. Finally, in 2050, heat pumps are the main source of energy for space and water heating, providing 49% of this heat demand, whereas electrical heaters are used to satisfy medium temperature industrial heat demand, and biomass and renewable electricity based SNG are used for high temperature heat demand in industry.

Energy demand of the heating sector in Kazakhstan is more than 4 times higher than the power demand accounted in final energy units, at the same time it is highly influenced by the harsh continental climatic conditions. This results in much higher storage system requirements of the power and heat integrated system. In 2050, 57% of all produced electricity and 24% of all produced heat have to be stored. Most of the energy is stored in short-term battery storage in order to guarantee the base load operation of PtG units and to satisfy energy requirement during winter times. The throughput of storage technologies and their shares in total electricity and heat output are presented in Figure 8.

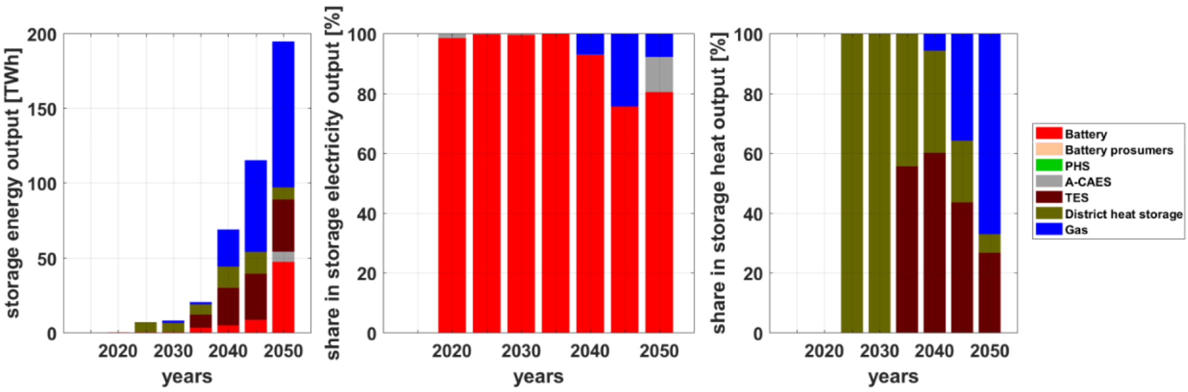

Figure 8. Throughput of storage technologies (left) and technologies shares in electricity (centre) and heat (right) output.

For the power system, battery storage plays the most important role, balancing daily generation variability. Only in later years gas storage starts to operate in order to balance seasonal variability of generation and temporal mismatch to demand. In the last year of transition, mid-term A-CAES storage emerges in the system to balance weekly variability and mismatch. However, even in 2050 battery storage plays the leading role by providing 80% of all stored electricity.

In the initial years of the transition, post the integration of district heating heat pumps, district heating heat storage is installed in order to maximise the efficiency of the space and water district heating system. Later, with the integration of electrical heating for industry, thermal energy storage is also installed. In later years of the transition, with decommissioning of coal-based heat and overall high GHG emission costs, gas storage starts to provide SNG for industrial high temperature processes.

With integration of the heating sector, heat storage is not used anymore for electricity generation, the heat becomes more valuable as a final product, which is quite a remarkable inversion of the value of heat at the beginning of the transition. At the same time, with the heat electrification, power sector demand becomes relatively much smaller than power generation and all reasons to produce power from heat disappear, which is also driven by the larger power generation.

Further integration of energy sectors will lead to even higher efficiency of the system: excess electricity and excess heat produced in the system with higher share of RE power and heat generation will become valuable energy source for industrial feedstock and transport sectors leading to lower energy cost, at the same time storage and distribution grids are used more effectively which also decreases the overall system cost [67, 68]. Another example for higher energy system efficiency of a Smart Energy System is CO_2 direct air capture [69], which is important for power-to-fuels and power-to-chemicals, since a major share of the required energy is thermal energy of about 70-100°C which can be at least partly sourced from excess and waste heat thus improving the overall energy system efficiency [70].

RE resources of Kazakhstan are sufficient to build a 100% RE power and heat system, even in the prevailing harsh climatic conditions. Even with much higher storage requirements due to seasonal heat demand variations, such a system can be economically feasible with power LCOE around 56 €/MWh and heat LCOH around 45 €/MWh in 2050. Figure 7 shows the LCOE and LCOH development during the transition for the power and heat integrated system scenario.

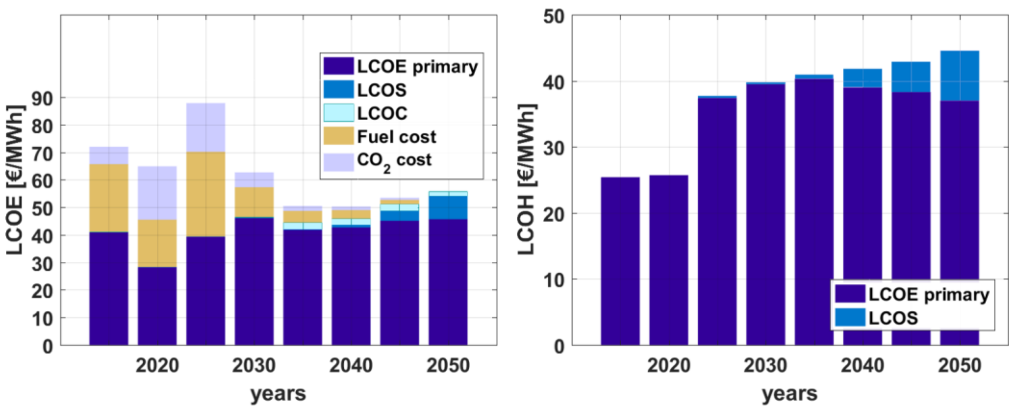

Figure 9. LCOE components (left) and LCOH (right) during transition.

From Figure 9, it can be seen that the LCOE development during the transition, as well as the LCOE components structure are similar to the power sector transition case. However, there are some variations. In particular, a higher cost increase in 2025 can be observed due to a faster growth of electricity demand along with the massive old power plants decommissioning. Another major deviation is due to slightly higher LCOE in 2050, power and heat sectors integration results in total LCOE of around 56 €/MWh in 2050, 2 €/MWh higher than in the power only scenario. The main reason is a higher share of more expensive wind power in the generation mix, which is needed for a better support of electricity-based heat supply during the winter seasons. At the same time, heat related storage costs are allocated to LCOH because most of the system balancing is made for the heat sector and that decreases the respective LCOS component of the power sector. Substantial PtG capacities are built in 2040 to 2050 that increase the total cost of the system and this results in slightly higher values for both LCOE and LCOH in 2050. LCOH is almost constant in 2015 and 2020 on the level around 25 €/MWh, due to low GHG emission costs and presence of fossil-based CHP plants, but later, with the decommissioning of CHP and a continuous increase of the GHG emission costs the LCOH slightly increases to reach 45 €/MWh in 2050. Despite the fact that in the 100% RE system heat becomes the product of electricity conversion, heat costs are still remarkably low because of the vast heat pumps utilisation. After 2050, LCOE and LCOH are expected to decline because of continuing cost decrease of RE and storage technologies. For the financial and technical assumptions of the year 2050 the LCOE would decline in the following periods by about 17% to about 46 €/MWh, the LCOH would decline by about 10% to about 40 €/MWh.

CONCLUSION

Results clearly show that the ambitious target to build a 100% renewable energy system in Kazakhstan is achievable. A 100% RE power and heat system can be built by 2050, substantially exceeding the country's «green concept» goal of 50% RE in the same time frame. That means, a 100% RE system will be most likely also feasible in any other region of Eurasia and other regions with similar climate conditions, since the case of Kazakhstan exhibits the harshest climatic conditions in Eurasia. However, the example of Kazakhstan shows that a transition towards 100% RE system can face some issues. Decommissioning of aging coal power plant capacities, induce challenges for a quick replacements. Most of these capacities were built in the pre-1990 era and reach the end of their lifetime around 2025, which can provoke a system shock due to fast fossil capacities phasing out and phasing in of the new RE capacities. This sharp change of the system structure may provoke a short-term spike in electricity costs due to an increased share of capital costs in the total levelised cost of electricity. Nevertheless, for the power only and integrated scenarios' electricity cost shows the trend to decrease while increasing the RE shares: from 74 €/MWh in 2015 to 54 €/MWh in 2050 for the power scenario and 56 €/MWh in 2050 for the integrated scenario. For both scenarios solar PV will become the main energy source, generating more than 50% of energy in the system (52% for power only and 56% for power and heat scenario), the wind energy share will be on the level of 30% for power only and 40% for the integrated scenario. Remaining energy will be provided by hydropower and biomass plants.

With an increase of the RE shares in the system, the demand for storage grows. The variability of RE sources and the continental climate of Kazakhstan implies a high storage throughput – in 2050 around 20% of all electricity demand is cycled through storage facilities. For power and heat sector coupling, integrated storage becomes even more important, as more than 50% of electricity and 24% of heat have to be stored to compensate heat demand variability under harsh continental climatic conditions. Most of the stored electricity is later on converted to heat, in particular seasonally. More batteries are used for increasing the electrolyser full load hours in the summer months via shifting solar PV electricity into the night hours and respective seasonal storage via power-to-gas and for increasing the FLh of heat pumps during the winter; both reduces the total energy system costs. From the storage capacity point of view, gas storage is the biggest storage in the system, however, throughput of battery storage is much higher, comprising 58% and 80% of total storage electricity output in the power sector scenario and integrated scenario, respectively. Further integration of transport and industrial feedstock sectors can lead to even higher system efficiency and thus lower overall energy cost.

Other regions of Eurasia have comparable solar and wind resources, and also significant hydropower and biomass potentials. The climatic conditions in most of the regions are more balanced than in Kazakhstan. All these factors position Kazakhstan to be a very good proof of possibility to realise a 100% renewable and sustainable energy system in Eurasia. These regions will face the same inherited problems: aging of existing capacities, huge storage requirements due to climate conditions, which will provoke some problems for the energy transition process. But, all the issues can be solved and a sustainable 100% renewable and low cost energy system can be created even in the near future.

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APPENDIX A. SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found, in the online version, at: e-component of the submission (link on the last page of the combined submission document).

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