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Impact of future energy policy on water resources in Kazakhstan

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ABSTRACT

As part of its strategic economic and social plan, Kazakhstan has a target of increasing the share of renewables and alternative energy sources in power generation to 50% by 2050. This greatly contrasts with the current situation, where around 90% of electricity is produced from fossil fuels. To achieve the target, the introduction of between 600 and 2000 MW of nuclear power is expected by 2030. This would impact water resources, already under stress due to significant losses, heavy reliance on irrigation for agriculture, unevenly distributed surface water, variations in transboundary inflows, amongst others. This study presents an integrated analysis of the water-energy systems in Kazakhstan, to investigate the water resource availability to support such energy system transition.

1. Introduction

Kazakhstan has vast reserves of oil, gas, coal and uranium [1], which the country utilises to produce around 90% of its electricity [2]. Recently, as part of its strategic economic and social plan, the government set out an ambitious target of increasing the share of renewables and alternative sources of energy in its power generation mix to 50% by 2050 [3]. While the transition to a green economy provides a unique opportunity to improve the sustainability of the national energy system, major natural resource challenges currently faced in the country should be taken into account.

Given that Kazakhstan is one of the most water scarce countries on the Eurasian continent [4], water resource management is of critical importance. The current water resource system is already under stress due to significant losses, heavy reliance on irrigation in the agricultural sector, unevenly distributed surface water, vulnerability to climate change and heavy dependence on transboundary inflows, amongst other issues [5–7]. Agriculture is the major water resource user, accounting for around 70% of the total withdrawal. However, due to inefficient irrigation practices and losses in the water transportation network [8], a significant part of the total use is losses. Industry, including the energy sector, and public supply respectively account for around 26% and 5% [9] of the remaining water withdrawal. The availability of water resources in Kazakhstan is heavily reliant on transboundary inflows, with 45% of the stored water resources in the country formed outside of its boundaries [4] flowing into the Irtysh, Ili, Chu, Talas, Ural and Syr Darya rivers. These inflows are projected to decrease by 30% per year by 2030 [8]. Moreover, the reliance on transboundary inflows from neighbouring countries has been a source of geopolitical tensions in the past [10,11] and all of these issues could be potentially exacerbated, given the vulnerability of the region to the effects of climate change [12].

Even though the water resources are scarce and not efficiently managed, the continuous provision of energy, which relies on availability of water resources, is important to the economy and the sector will continue to expand as the country continues to pursue its targets towards higher development standards. While several government policies on water and energy resources have been proposed for each of the sectors, the two systems are mostly treated separately. As a prominent example, water resources have not been considered in the National 2050 Low Carbon Energy Strategy. This is a significant omission, given the high amount of water required in the energy sector for extraction, refining and cooling purposes [13,14].

The high share of fossil use in the power sector in Kazakhstan has significant implications on water withdrawals, which are required throughout the life cycle of thermoelectric power production. This

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includes fuel extraction, operation of cooling systems in power plants, and infrastructure dismantling [15]. Currently, approximately 18% of freshwater withdrawals in the country are used for cooling thermo-electric power plants, where closed-loop systems are commonly used [16]. Considering that energy consumption is predicted to increase by over 50% in 2030 relative to 2005 [17] and given the existing stress on water resources, the interactions between the energy and water systems have become key challenges to sustainable development in Kazakhstan.

The key question we address in this work is whether water resource availability in Kazakhstan would be adequate to support the transition to a green economy, with a new energy system, without compromising other important water uses and ecosystem services. Given the challenges mentioned above, it is clear that tackling this question requires an integrated analysis of the water-energy systems. We seek to address this question considering two main objectives: (1) Analyse current and future water requirements for the energy system per basin; (2) Use the output of the analysis in (1) to assess whether the changes in the energy system and the associated water requirements will have impact on the availability of water resources for other sectors.

This paper is structured as follows: Section 2 provides a review of the current situation in the water and energy resources, government projections and initiatives for both sectors and the details of the methodology, including data sources, description of scenarios, and data analysis methods; Section 3 presents the results of the analysis and a discussion on the significance of the results; and Section 4 provides conclusions and pointers to future research needs for a better understanding of the energy-water nexus in Kazakhstan.

2. Methodology

To determine the implications of Kazakhstan's current and future energy system configuration for water resources, this study maps the interactions between the water and energy systems, and estimates the associated current (2014) and future (2040) water requirements. This study specifically analysed water use in: the extraction of coal, oil, natural gas and uranium; oil refining; and thermal power generation (including proposed new nuclear plants). This is accomplished in three stages: (1) Review of the current situation and mapping of the current linkages between the energy sector and water resources; (2) estimation of the current water requirements for the energy sector at the river basin scale; and (3) estimation of future water resource requirement for the sector in 2040 across each river basin based on government projections, and considering two scenarios of nuclear power plant location – the energy pathways considered are based on information from the literature, and not modelled specifically for this study. The results of the analysis are then compared to the water availability in each of the major river basins in the country to identify regions which could be most impacted by the transition to a new energy system. The base year of 2014 is chosen to make use of the most current publicly available data on energy and water resources, while 2040 was chosen to coincide with the timeframe commonly used in government projections for the energy system transitions [2]. Potential impacts of climate change are not taken into account in this study.

2.1. Current situation and linkages between water and energy in Kazakhstan

The territory of Kazakhstan contains 8 main river basins: Aral-Syrdarya, Balkhash-Alakol, Irtysh, Ishim, Nura-Sarysu, Shy-Talas, Tobol-Turgai, and Ural-Caspian [18]. Tobol-Torgai and Nura-Sarysu account for 21% of the country's total population and approximately 35% of the total arable land but have only 3% of the total water resources in the country. The Irtysh, Aral-Syrdarya and Balkhash-Alakol river basins account for almost 75% of the water resources generated within the country. The western part of Kazakhstan (Ural-Caspian basin), the oil and gas province of the country, depends significantly on groundwater and water desalination, contributing around 30–35% of the total water supply, as a source of drinking water and irrigation, with the remaining 65–70% from surface water [9]. The availability of water resources is particularly low in the river basin of Tobol-Turgai, which often experiences water shortages, and Nura-Sarysu, where the low water resources need to be complemented by a canal from the Irtysh river.

The energy sector of Kazakhstan is largely dominated by fossil fuels, with vast reserves of coal, gas, and oil. There are currently 76 power plants with an installed capacity of 20.5 GW, including 18.1 GW from thermal power plants, and 2.4 GW from hydroelectric power plants [2]. The majority of the thermal power plants are coal-fired, accounting for 68% of total electricity generation. Gas-fired plants account for around 20%, while the remaining generation is met by hydropower (around 10%) and a small contribution from renewables [2].

The industry sector accounts for the highest electricity demand in the country (around 70% of total energy consumption in 2014) [19]. For this reason, the location of the majority of the power plants reflects the geographical distribution of industry, with a high proportion being located in the north and eastern parts of the country. The industry sector is highly energy-intensive, and uses two to three times more energy than the average for developed OECD countries [20]. Thus the potential for energy savings in Kazakhstan's industrial sector is significantly high [21].

The current use of water in the energy sector is mainly underlined by the extraction of coal, oil, natural gas, and uranium, crude oil refining and thermo-electric cooling. Water withdrawals for power station cooling, in particular, present a major challenge because spatial patterns of energy and water availability do not match those of resource demand and economic and social development [22]. Around 80% of total electricity is produced in the industrial north by power plants located near coal mines in Irtysh and Nura-Sarysu river basins [23] which leads to relatively high water withdrawals for cooling in these basins.

Kazakhstan is aiming to reduce carbon emissions per unit of GDP in 2020 by 15% and 25% by 2050 compared to 1992 levels [19]. In order to meet these goals and provide access to sustainable energy services, the country is aiming to reduce the share of coal in its energy mix. The National 2050 Low Carbon Energy Strategy (Directive No. 577 of 30.05.2013) seeks to raise the share of total energy consumption supplied by renewable energy sources (50% of electricity must be supplied by renewable energy sources by 2050) and natural gas. Nuclear energy is also expected to play an important role in Kazakhstan's transition to a low-carbon energy future, with plans to build a nuclear power plant with a capacity between 600 and 2000 MW by 2030. The period of implementation for this project is expected to be between 2020 and 2030. This is likely to have a significant impact on water resources as nuclear electricity generation requires large amounts of water for cooling.

2.2. Estimation of current water requirements for the energy sector

The approach used in this study for the estimation of water requirements for the energy sector is in line with the methodology used in various water-energy nexus studies [16,24–26], in which the authors estimated water requirements based on the primary fuel type, mode of extraction, refining processes and conversion and cooling technology used. The energy sector technologies are therefore mapped and disaggregated under these key categories at the national level. However, whilst key energy sector policies and plans are usually taken at the national/regional level, water resource required for implementing such plans and the potential associated impacts are best analysed at the river basin level where actual withdrawals take place [24]. Additionally, due to the disproportionate spatial distribution of water resources, national level analysis may not reveal key potential stresses posed by the energy sector in water-poor basins of the country. Thus, in this study data for energy and water was collected and analysed at the basin scale, and involves the eight main river basins of the country.

The current water required for the extraction of both underground and surface-mined coal, for onshore oil and gas, and for extraction of uranium via in-situ leaching (ISL), were estimated based on annual production data from a combination of national statistics [2] and other energy extraction industry and organizations [27–29] and water use coefficients per unit of extracted resource [30]. Similarly, water requirements for refining were estimated for the production of petroleum products and coal washing processes using the above methodology. Water requirements for power generation were estimated by combining data for individual power plants including the technology type, primary fuel use and cooling technology, with the annual electricity production data and the water use coefficients associated with these technologies. The sources for these data include national and information from websites of Kazakhstan utility companies [31–36]. The cooling technologies for each power station were identified using data published by the individual plants and satellite imagery from Google Earth and Bing Maps. As there is currently no publicly available data on specific water used by cooling technology types in Kazakhstan, this study employs water use coefficients for different technologies published in various studies for power generation in China [30], which is assumed to offer the best available estimates in terms of age of power plants, geography and climatology.

2.3. Estimation of future water requirement for the energy sector

The estimation of future water requirements for the energy provision across the key river basins in Kazakhstan follows the same approach used in estimating current water resources, but incorporates key assumptions of the evolution of the energy sector based on government projections, plans and projected population growth and associated demand increases, as presented in the report “The National Energy Report 2015″ produced by KazEnergy [2]. According to this report onshore oil and coal extraction is projected to decrease by 12% and 20%, respectively, by 2040 while uranium production is assumed to remain the same as in 2014. In the petroleum-refining sector, the three main oil refineries in Kazakhstan are assumed to continue operating in 2040, with a capacity increase of 20%.

In the electricity generation sector, the total thermal generation capacity fuelled by fossil resources is projected to remain approximately the same as in 2014. However, the share of gas generation is projected to increase to 31% and coal decreased to 50% of total generation. This assumption is predicated on the Kazakh government's ambitious plans to significantly reduce carbon emissions per unit of GDP of the energy sector by 25% in 2050. The additional capacity required to meeting future demands is projected to be provided by the introduction of 1.2GWe nuclear generation and a small share of wind (the business as usual scenario for 2040 includes 3 GW of new wind capacity). The hydro generation is projected to increase by less than 10% from 2014 to 2040, with this increase in capacity occurring along the same basins as the existing capacity in 2014. Fig. 1 shows the electricity mix for 2014 and 2040 considered in this study.

Future power stations are generally assumed to be located in the same river basins as today, except the planned new nuclear power plants, for which two location scenarios are considered: Ulken in the South (Balkash-Alakol basin) and Kurchatov in the Northeast (Irthysh basin) and some of the new gas and coal power stations whose locations are dependent on the location of the new nuclear power plant, in accordance with the “The National Energy Report 2015" [2]. This has been used as the basis to define two future energy scenarios that coincide with the potential locations currently under consideration by the government: 2040a, with the nuclear power station located in Ulken and 2040b, with the nuclear power plant located in Kurchatov. In terms of cooling technologies, the study considers a business as usual scenario that assumes the deployment of the same types of current technology in future. The distribution of cooling technologies used in power plants per primary source within each basin is presented in table A1 in the supplementary information. Since our business as usual scenario assumes no change in technologies, the cooling technologies used in thermal power plants of each type in 2040 are assumed to be the same as in 2014 To estimate the water stress imposed by the energy sector on water resource at the basin level, this study estimated the percentage of available resource that is deployed for energy provision.

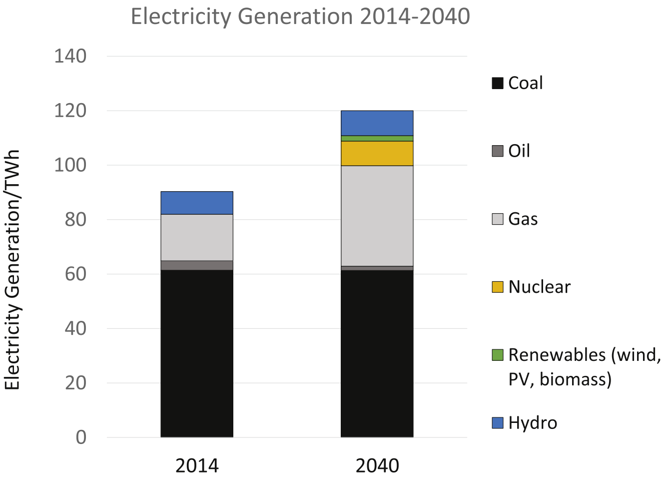

Fig. 1. Current and future electricity generation in Kazakhstan. Source: “The National Energy Report 2015” [2].

3. Results and discussion

The results are presented in three main parts. The first part presents the resource extraction and refining and electricity generation per basin in 2014 and 2040. This is followed by the results of the analysis of the current and 2040 water requirements for the energy system per basin. Finally, the output of the comparison of the water requirements for the energy system with the total renewable water resources per basin are presented.

3.1. Resource extraction, refining and electricity generation per basin

Given the characteristics of the Kazakhstan energy system in 2014 and 2040, the main uses of water resources in the energy system considered in this study are those used in the extraction of coal, uranium, oil and gas, crude oil refining and thermal electricity generation. In order to estimate the total water withdrawals per basin, the production of energy resources, oil products in refineries and generated thermal electricity per basin, were estimated in the first step of this study. As most of the energy extraction data from the main bibliographic sources were categorized by oblast, the available data were used in combination with a GIS analysis of the geographical limits of the basins to allocate coal and uranium mines, oil and natural gas extraction sites, refineries and power plants and associated production to specific basins. The results of this allocation for 2014 and 2040 for extraction of the different energy resources and crude oil refining are presented in Table 1 to Table 4. The results for the allocation of the thermal electricity generation by primary resource and by basin in 2014 and 2040 are shown in Fig. 2, considering the two scenarios that arise from the alternative locations of the nuclear power plant, 2040a (Ulken) and 2040b (Kurchatov). Overall the results show that energy resource extraction, refineries and power plants are unevenly distributed throughout the basins, which leads to different levels of impact on water resources, as these are also not uniformly distributed.

The results in Table 1 show that coal extraction is concentrated around the Irtysh and Nura-Sarysu basins (corresponding to the

Table 1
Coal extraction (in TWh) in 2014 and 2040.

Water basin	Type	2014	2040
Ishim	Open-pit	11.2	7.9
Aral-Syrdarya	Open-pit	35.8	25.3
Nura-Sarysu	Open-pit	147.5	104.4
Nura-Sarysu	Underground	50.3	35.6
Tobol-Turgay	Open-pit	0.0	47.2
Irtysh	Open-pit	314.8	222.7

exploration of reserves in the Karaganda and Pavlodar oblasts), mainly from open-pit mines, with the only underground mine considered in this study located in the Nura-Sarysu basin [2]. Total coal extraction is projected to fall between 2014 and 2040 for all basins, except for the Tobol-Turgay basin. Similarly, uranium reserves are also aggregated in

Table 2
Uranium Extraction (in tonnes of Uranium) in 2014 and 2040.

Water Basin	2014	2040
Irtysh	3155.06	3155.06
Shu-Talas	10913.06	10913.06
Aral-Syrdarya	8188	8188
Ishim	698	698

Table 3
Oil extraction (in TWh) in 2014 and 2040.

Water Basin	2014	2040
Ural-Caspii	825.2	864.8
Aral-Syrdarya	115.2	69.8

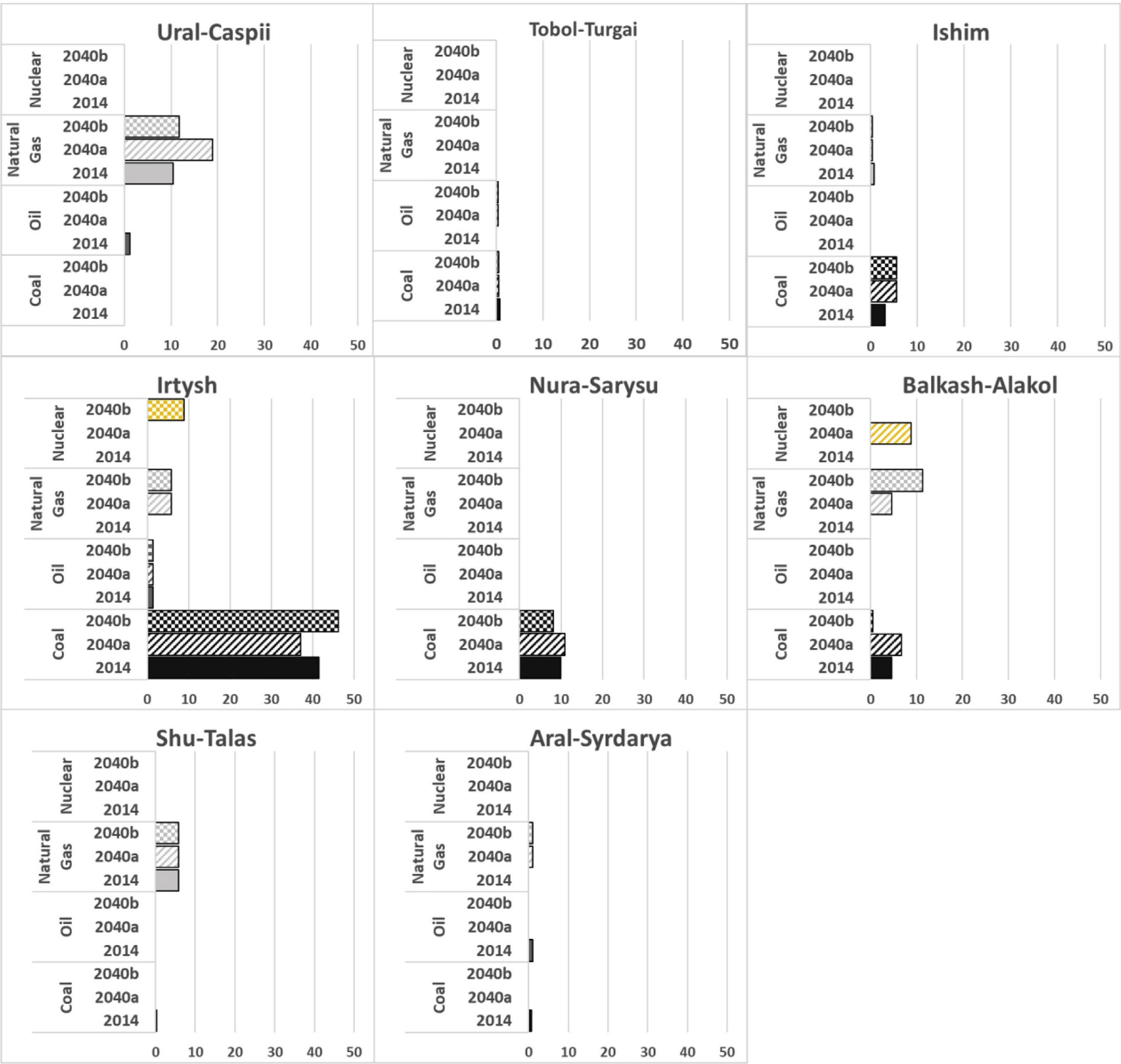

Fig. 2. Current and future thermal electricity generation (in TWh) by basin, considering two alternative locations for the nuclear power plant: Ulken (2040a) and Kurchatov (2040b).

Table 4
Crude oil refining (in TWh) in 2014 and 2040.

Basin	2014	2040
Shu-Talas	61.7	62.9
Irtysh	57.0	71.0
Ural-Caspii	57.0	76.8

a small number of sites, located along the Shu-Talas, Aral-Syrdarya and Irtysh basins (Table 2). Yearly uranium production is assumed constant between 2014 and 2040. Oil extraction, and accompanying natural gas, is mainly concentrated in the Ural-Caspii basin, with a smaller share of extraction occurring in the Aral-Syrdarya basin (Table 3). Levels of crude oil production are expected to increase slightly in the Ural-Caspii basin while decreasing significantly in the Aral-Syrdarya basin. Crude oil refining occurs in three main refineries located respectively on the Shu-Talas, Isthysh and Ural-Caspii basins (Table 4), with levels of production of oil products projected to increase significantly from 2014 to 2040 in the Irtysh and Ural-Caspii basins, while remaining relatively unchanged in the Shu-Talas basin.

Fig. 2 shows total thermal electricity generated by primary source and by basin, for the base year and the two alternative 2040 energy system configurations. The results show that most of the electricity thermal coal generation, in the base year and future, is located in the Irtysh basin. This basin is home to a major industrial centre that represents a significant share of the overall electricity demand. Most of the remaining coal capacity located in the Nura-Sarysu, Ishim and Balkash-Alakol basins. Nuclear electricity generation could also play a significant role in the Irtysh basin, in case the Kurchatov site if chosen for the nuclear power plant. The alternative location for the nuclear power station in Ulken would lead to a very significant increase in the levels of electricity generation in the Balkash-Alakol basin. The projected increase of capacity in this region is mainly aimed at providing for increased demand from the domestic sector. Natural gas generation is mainly located in the Ural-Caspii and Balkash-Alakol basins, with a projected increase in electricity generation in both basins and for both future energy scenarios.

3.2. *Analysis of the water requirements for the energy system per basin*

The water requirements for the energy system in 2014 and 2040, taking into account the allocation of energy resource extraction, refining and electricity production to the different basins are presented as Sankey diagrams in Fig. 3 and Fig. 4, representing the two alternative future energy system configurations. Further details of the cooling technologies by fuel source and basin can be found in Table A2 (supplementary material). The Sankey diagrams show the total water withdrawals for the energy system disaggregated into extraction, power generation and refining, by basin in 2014 and in each of the future energy scenarios. Generally, electricity generation is responsible for over 90% of the water requirements for the energy system and the Irtysh basin has the highest overall water withdrawals. The results show an increase in total water withdrawals for both future energy scenarios, with the bulk of the increase taking pace in the power generation sector, although this increase is not uniformly distributed amongst the basins (see Fig. 5).

The results for the 2040 energy system configuration that stems from a preference for the Ulken nuclear location (2040a) is shown in Fig. 3. The most significant change in water withdrawals occurs in the Balkash-Alakol basin, where the water requirements increase approximately by a factor of 14 relative to the base year. This is mainly due to the nuclear power plant siting in this basin and the assumption that the cooling technology is a once-through system.

Fig. 4 shows the results for the 2040 energy system configuration that stems from a preference for the Kurchatov nuclear location (2040b) in the Irtysh basin. The most significant change in water withdrawals occurs in the Irtysh basin, where the water requirements increase by approximately 60%. Similarly to the other future energy scenario, this is mainly due to the nuclear power plant siting in this basin and the assumption that the cooling technology is a once-through system.

3.3. *Comparison of the water requirements with the total renewable resource available per basin*

Finally, in order to determine whether the energy system water requirements in the base year and 2040 represent a significant stress on the water resources, the overall level of water withdrawals were expressed as percentages of the total renewable water resources available in each basin. The results are presented in Fig. 4, where only requirements that represent a share above 5% of the total renewable water resources are shown. Overall, the results show that water withdrawals for the energy system are very significant in Nura-Sarysu, representing approximately 60% of the total renewable resources in the basin. The results show that this impact is decreased if the Kurchatov site is chosen for the new nuclear generation. However in both scenarios the withdrawals for the energy system constitute a significant share of the available water resources in the basin. The energy system also represents around 10% of the total renewable water resource in the Irtysh basin in 2014, with the nuclear power plant leading to an increase of this share to approximately 16%. This is particularly significant as the Irtysh river has a significant share of international transboundary flows. The impact of the nuclear power plant in the Ulken site is also shown through the significant increase of the share of water resources that is allocated to the energy system in Balkash-Alakol basin when this site is chosen.

4. Conclusions

The study had two key objectives, first, to analyse the current and future water requirements for the energy system per basin, and second, to assess whether the changes in the energy system and the associated water requirements will have impact on the availability of water resources for other sectors. From the output of the analysis presented it can be concluded that the current energy system of Kazakhstan requires a significant amount of water resources for the operation, especially for power plant cooling, and future changes would further increase these demands. However, the overall impacts on renewable resource availability differs from basin to basin and therefore by extension the impact on other sectors depends on the basin under consideration.

It has been shown that the development of the energy system in Kazakhstan can greatly reduce the water available for other sectors at the basin level (case in point Nura-Sarysu). This presents an opportunity to plan long term changes in the energy system with the specific aim of reducing the impact on the water stressed basins. This could be achieved by: (1) allocating less water intensive power generation capacity to the basin; or, (2) by choosing power plant cooling technologies that require less water – e.g. air or hybrid cooling.

This study has also shown that the future changes in the energy system of Kazakhstan are likely to have a significant impact on regions that are highly dependent on transboundary water resources. As mentioned in Section 1, around 45% of available water resource originates from transboundary inflows, which are projected to decrease by as much as 30% by 2030. Considering that the proposed locations of the new nuclear capacity are within transboundary basins, namely Ulken in the Balkash-Alakol and Kurchatov in the Irtysh, changes in future inflows could significantly affect the operation of these power plant units. For instance, with the energy scenario considering Ulken as the future location of the new nuclear capacity, water withdrawals in the Balkash-Alakol basin would increase by a factor of 14, relative to base year. On the other hand, opting for the Kurchatov site would lead to a 60% increase in water withdrawals in the Irtysh basin. Thus, this study shows

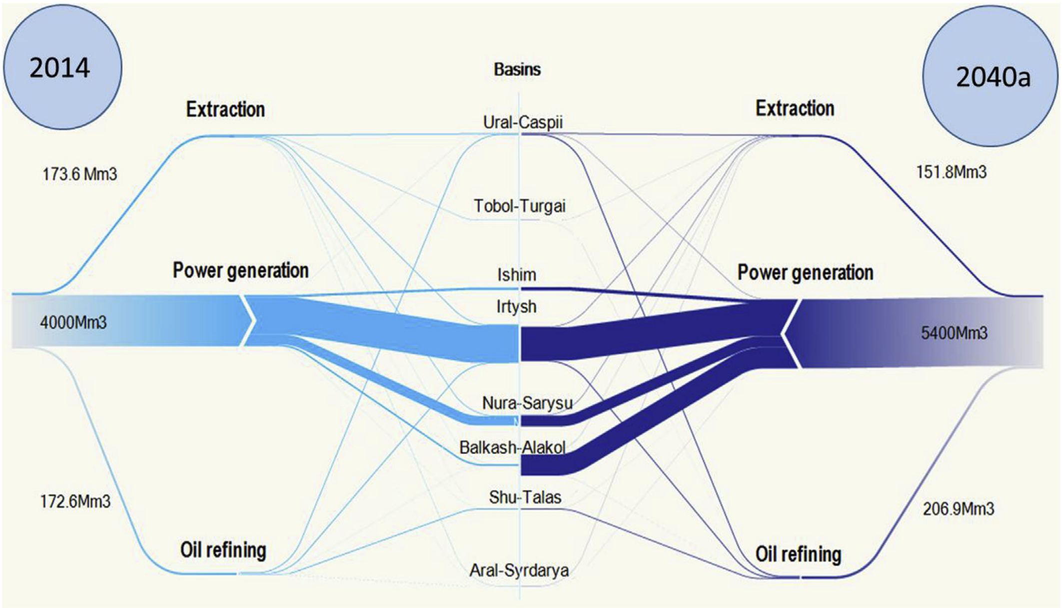

Fig. 3. Water requirements for the energy system in 2014 and 2040, for the Ulken nuclear power plant location.

that the choice of location of future nuclear power stations is crucial because competition for water in the proposed catchments may be significant and this could limit the amount of resources available for the efficient operation of the energy system.

The key problems highlighted by this study regarding future water requirements for the energy sector of Kazakhstan, coupled with the uneven spatial and temporal distribution of natural resources suggest the need for further studies that incorporate of the following:

(1) Scenarios of seasonal availability of water or irregular patterns of precipitation, both spatial and temporal (e.g. perform studies with different scenarios of water availability). This would provide insight on potential future water availability for all sectors and how withdrawal from the energy sector may contribute to water stress levels across different regions of the country. Additionally, this would highlight the impacts of climate change on energy system operation;
(2) Water and energy resource availability and demand should be analysed at higher temporal and spatial scale (bottom-up GIS analysis). This would allow for a more detailed analysis of any potential plant level water demand and supply dynamics as energy systems operate at high temporal resolution.
(3) The analysis of water and energy issues in Kazakhstan should be carried out within the context of water and energy policies of all the other countries in the region that share the water resources. This would allow the harmonization of water dependent energy and industrial policies in the region, thus avoiding potential conflicts and operational problems between countries sharing common resources.
(4) Expand the analysis to include water withdrawals by other sectors. This would reveal the key trade-offs between transitioning to a low-carbon energy systems that relies significantly on water intensive

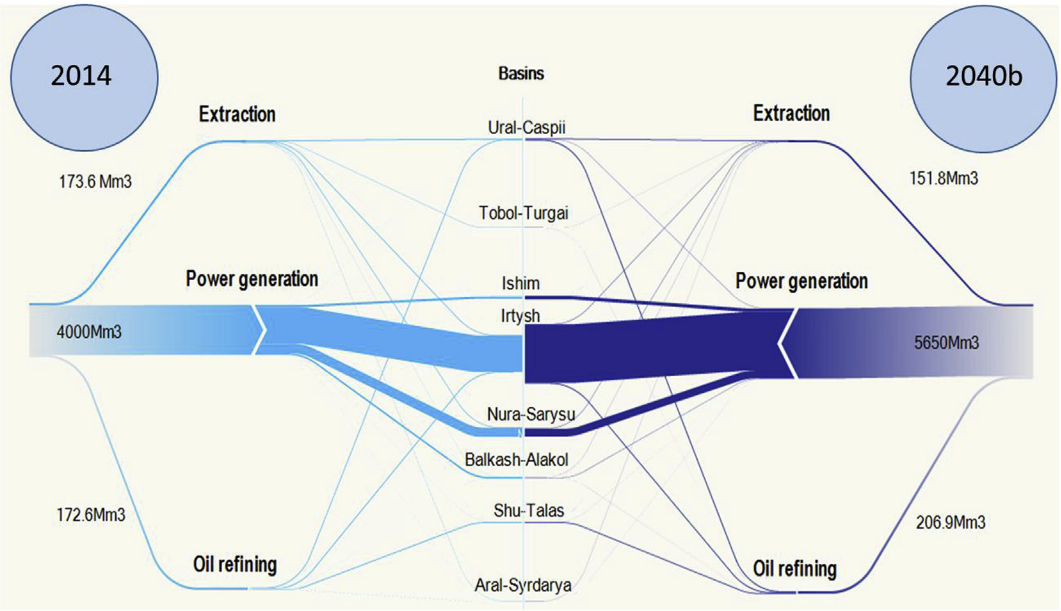

Fig. 4. Water requirements for the energy system in 2014 and 2040, for the Kurchatov nuclear power plant location.

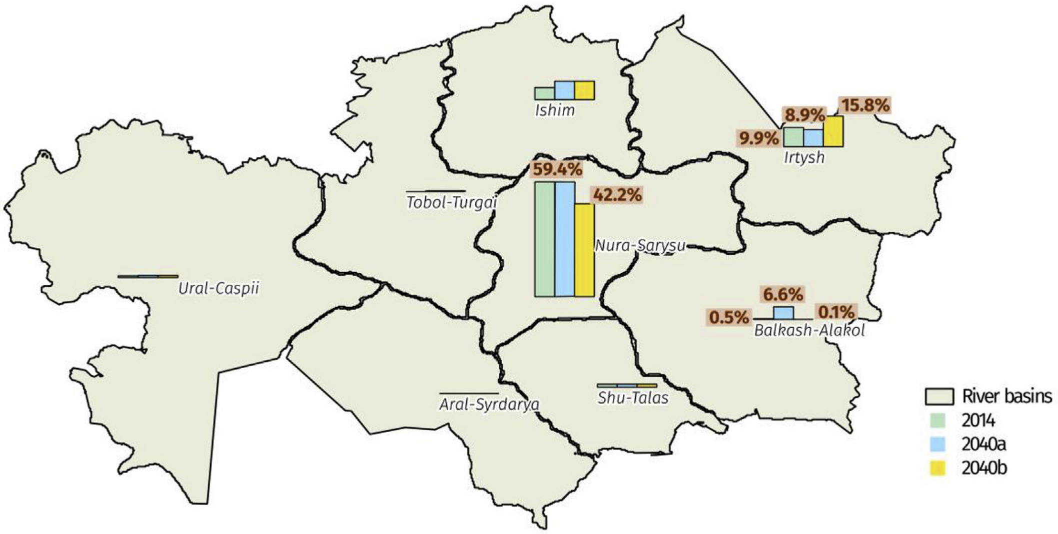

Fig. 5. Total water withdrawal as a percentage of renewable water resources per basin.

energy technologies and other industrial, domestic and ecosystem services.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2019.04.009.

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