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Water availability for bioenergy in Kazakhstan: Review, preliminary results, and key points

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ABSTRACT

In transitional countries with arid climates, water stress is rising as the demand for water rises with population, economic growth, and intensive development of agriculture and energy and change in climate environment. In this regard, transitional nations plan in national programmes and policies alternative energy sources, sustainable food development, and circular water resource usage. However, these nations frequently approach current water, energy, and food planning without taking interactions of these resources and their impact on each other into account. This paper intends to demonstrate the significance of the water, energy, and food nexus approach for Central Asian countries in transition. Kazakhstan is used as an example of a resource-rich, transitional economy in Central Asia. Kazakhstan has set a goal of reaching a 50% share of renewable and alternative energy sources in electricity generation by the year 2050 to reduce water and energy poverty, improve water and energy efficiency, achieve carbon neutrality, and rank among the top 30 developed nations. To meet the water and renewable energy goal, bioenergy plantation is anticipated to develop between 2030 and 2050. The findings of paper show that total withdrawals for bioenergy increase from the reported data of 15503.68 m^3 in 2020 to 32182.16 m^3 in 2050 under a bioenergy-intensive scenario. The average total increase, or 75.5%, would be 16678.48 m^3. As such, policymakers and stakeholders in Central Asian region and Kazakhstan needs to carefully design its national energy goals given its future increase of water withdrawals, and shortage environment.

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1. Introduction

In comparison to the global average, the availability of water resources in the Central Asian region is higher, however, according to international water monitoring data, the Central Asian region is classified as water stressed region, with water availability per capita between 1000 and 1700 m^3 cap−1 (FAO, 2018) and the future water situation under baseline development indicates serious stress on water resources and environmental systems in the region (Reyer et al., 2017; Baspakova et al., 2022). The impacts of climate change on the hydrological cycle and their implications for the future regional water situation are of particular concern (Malsy et al., 2012). As has been previously reported, the environment in Central Asia is changing quickly as a result of climate change (Salnikov et al. 2015; Kaldybayev et al., 2016). Surface water resources are the ones most affected by environmental changes, and they are particularly vulnerable in Central Asia because this region relies heavily on snow and glacier replenishment in the mountainous area (Sorg et al., 2012; Alimkulov et al., 2019; Chigrinets et al., 2020). It has been noted that the runoff trends of various surface water resources have changed dramatically (Olsson et al., 2010; Imentai et al., 2015). Moreover, due to outdated water facility infrastructure (Barrett et al., 2017), harmful water pollution (Nazhmetdinova et al., 2018), poor efficiency of usage and circular reusage of water in agriculture, energy, and industrial sector (Rivotti et al., 2019), imperfect system of water management, in particular legislative and institutional framework (Janusz-Pawletta, 2015), the Central Asian region has already suffered severe water losses, while in rural areas there is a limited access to clean and safe drinking water supply (Bolatova et al., 2021), which leads to further consequences on negative population health (Bekturganov et al., 2016).

In addition to the mitigation of climate change for providing water security, the chances for a shift from high-carbon to low-carbon energy to alternative low-carbon energy systems are viewed as vital for sustainability trends in environment systems including water sector (Mikulčić et al., 2021; Helerea et al., 2023). Modernized bioenergy systems are highlighted by several Central Asian nations (Kazakhstan and Uzbekistan) as a desirable choice for energy security and climate change mitigation (Mehta et al., 2021). Because it is inexpensive and can be used to make electricity, liquid, gaseous, and refined solid fuels, biomass is a desirable choice for reducing climate change in the energy industry (Souza et al., 2017). The energy systems based on biomass allow for the reduction of greenhouse gas emissions, the creation of new jobs, and the advancement of science and technology (Domac et al., 2005). However, a crucial factor in the production of large amounts of bioenergy is the availability and productivity of water resources (Gerbens-Leenes et al., 2009). Moreover, water is required for the final energy conversion of biomass into fuel, electricity, and heat

(Singh et al., 2011; Gheewala et al., 2011). In addition, in various ways, the bioenergy plantations change the amount of blue water that is accessible in rivers, lakes, and aquifers by changing the ratio between evapotranspiration and runoff (Berndes, 2002). Taking these arguments into account, the Central Asian region may, however, repeat historical mistake of mismatch between real policy and resource availability if it follows the global trend of using biomass (Rivotti et al., 2019). A well-known case of a mismatch between actual policy, effectiveness, and resource availability is the desiccation of the Aral Sea (Wang et al., 2020; Huang et al., 2022).

The Central Asian countries in transition, including Kazakhstan, lack research on how bioenergy transition would affect the future accessibility of water resources in Central Asia and Kazakhstan as a replacement for fossil fuels. Kazakhstan stands out in this context due to its water, energy, and food ambitions. To determine how much water is needed in Kazakhstan to sustain the development of the bioenergy industry for a transition from a high to a low-carbon energy system, this paper uses nexus-based scenario analysis and ArcGIS tool. The paper is structured in five sections. The section two presents main trends in water-energy-food sectors in Kazakhstan. The section three describes the data and method for estimation and mapping of bioenergy potential, scenario generation. The section four discusses the technical primary biomass potential for bioenergy and future water withdrawal to support bioenergy industry. The section five provides brief concluding key points.

2. Case of Kazakhstan

With a population of 20.2 million, Kazakhstan is a landlocked country in the Central Asia region (Table I). The average population density is 6 people per km^2, although it ranges from 2 people per km^2 in the Zhezkazgan province in the central part of Kazakhstan to 20 people per km^2 in the Almaty province in the south-eastern part of Kazakhstan (UN, 2022). By 2050, the total population of the country is expected to be 34.0 million, with an average annual growth rate of 1.1%. Kazakhstan's gross domestic product (GDP) was 190 USD million in 2021 (WB, 2022), and by 2050, it is expected to grow by 2.7%. Kazakhstan's actual growth depends on the state of the global economy and the stabilization of fuel prices. Kazakhstan has been severely impacted by outside shocks in 2015, such as falling oil prices. GDP growth fell from 4.1% to 1.2% between 2014 and 2015 (ADB, 2022). Kazakhstan's economy is dominated by industry, which includes the oil and gas sector, accounting for 44% of GDP while agriculture makes up 5% (WB, 2022).

Table I. Basic data and population (WB, 2022; UN, 2022)

Physical areas	
Area of the country	272 490 000 ha
Cultivated area (arable land and are area under permanent crops)	23 480 000 ha
as % of the total area of the country	9 %
arable land (temporary crops)	23 400 000 ha
area under permanent crops	80 000 ha
Precipitation	250 mm per year
Population	
Total population	20 210 000 inhabitants
of which rural	45 %
Population density	6 inhabitants per km^2
Economy and development	
Gross Domestic Product	190 223 mln USD per year
value added in agriculture (% of GDP)	5 %
GDP per capita	10 041 USD per year
Access to improved drinking water	
Total population	95 %
Urban population	99 %
Rural population	90 %

In international reports, Kazakhstan continues to be a former Soviet nation with abundant natural resources. Kazakhstan is frequently referred to be a petrostate or a resource-rich nation (Karatayev & Hall, 2020). The country's natural gas reserves are estimated to be 842 Mtoe (11.2 Mtoe annual production), while its proven oil reserves are 3.93 billion tons, making Kazakhstan the world's 17th largest oil producer (79.3 million tons of current production). According to national and international estimates, despite the expected increase in output, there are sufficient reserves for 50-70 years of production. Despite having large oil and gas reserves, Kazakhstan uses coal for domestic energy consumption and exports the production of oil and gas resources to the EU and China. Kazakhstan has the 7th largest coal producer in the world, with total recoverable reserves estimated at 23.5 Mtoe. According to a government estimate, reserves will endure for 300 years at 2020 production levels of 74.5 Mtoe (ECT, 2020). Currently, coal power plants, which are predominantly based in Kazakhstan's north and center, generate 85% of the nation's total electricity.

Despite the existence of sizable energy resources and advancements in assuring energy security (as a result of the development of new projects in the oil and gas sector), Kazakhstan still has issues that need to be addressed. These issues include energy poverty in most rural regions, significant levels of environmental pollution from the energy sectors, and inefficient technologies in the coal industry (Mukhamediev et al., 2019; Mukhtarov et al., 2020). These factors led Kazakhstan to create an energy transition plan. Kazakhstan has agreed to aggressive water, energy, and food targets (Table II). By 2050, Kazakhstan aims to raise the use of renewable energy by 50%, cut carbon emissions by 40%, and enhance energy efficiency by 50% (ECT, 2020). Regarding the predicted future profile of renewable energy sources, the Ministry of Agriculture has developed a plan for the establishment of bio-energy plantations using bioenergy crop species. However, this plan lacks an examination of the impact of this biomass development plan on water availability.

Table II. Water, energy, and food targets (Karatayev, 2021)

Strategic document	**Policy targets**	**Indicators**	**Nexus sectors**
National Plan on Integrated Water Resources Management until 2025 (Decree No 67 of 28.01.2009)	Adoption of water river basin approach and reduction of water lost in agriculture	30% by 2025 8 River Basin Councils based on hydrological boundaries	Water
National Water Program “Ak Bulak” until 2020 (Decree No 1176 of 09.11.2010)	Providing reliable access to water resources	100% by 2020 in urban areas 80% by 2040 in rural areas	Water
Program of Development of Nuclear Power (Decree No 728 of 29.06.2011)	Increasing the share of nuclear power in the national energy mix	Nuclear power plant with a capacity from 900 to 2,000 MW by 2030	Energy
National Green Economy Concept (Decree No 577 of 30.05.2013)	Reduction of GDP energy intensity	25% by 2020 30% by 2030 50% by 2050	Energy
National Green Economy Concept (Decree No 577 of 30.05.2013)	Development of RES through the construction of wind, solar, biomass and small hydro power facilities	3% by 2030 50% by 2050	Energy
Concept of Developing the Fossil Fuel and Power Generation Complex up to 2030 (Decree No 724 of 28.06.2014)	The increase in volume of fossil fuel production for national energy security	Coal: 113 Mt per year by 2030 Oil: 118.1 Mt per year by 2030 Gas: 59.7 bn m^3 per year by 2030	Energy
State Program on Water Resources Management (Decree No 786 of 04.04.2014)	Reduction of water consumption per unit of GDP	Level of 2012 - 33% by 2020 - 77% by 2040	Water
State Programme on Agricultural Development (Decree No 423 of 12.07.2018)	Reduction of irrigation water consumption	Level of 2017 -15% by 2021	Water
State Programme on Agricultural Development (Decree No 423 of 12.07.2018)	Increasing wheat productivity	Level of 2017 +60% by 2030 25% of areas with efficient technologies	Food
New Concept for State program on Water Resources Management for 2020-2030 (28.01.2020)	Reduction of water consumption per unit of GDP	Level of 2018 - 20% by 2030	Water
New Concept for State program on Water Resources Management for 2020-2030 (28.01.2020)	Increasing the irrigated agriculture land	43% by 2030	Food
New Concept for State program on Water Resources Management for 2020-2030 (28.01.2020)	Increasing the length of lined water pipeline	from 3 423 to 19 000 km	Water

Water security seems to be a concern for all countries (Birkás et al., 2021), but it is a deep concern, especially for Kazakhstan, as water resources are unevenly distributed in the country. In addition, a significant amount of water resources (56%) is formed outside of Kazakhstan (Karatayev, 2021), which makes the country dependent on China, Russia, Uzbekistan, and Kyrgyzstan. Kazakhstan has a lower per capita water availability than the global average (Table III). In Kazakhstan, there is a water availability of 37000 m^3 per km^2 and 6000 m^3 per capita annually (Table IV). Many rural areas of Kazakhstan are experiencing water scarcity, and despite numerous projects sponsored by international donors (ADB, 2020), the situation is not leading to progress (Barrett et al., 2017). Currently, the country withdraws 20.18 km^3 of water, of which 14.76 km^3 or 66% is used by the agriculture sector (Table V). The use of water resources in agriculture remains inefficient and unsustainable (UNDP, 2021).

3. Data and method

Estimation of bioenergy potential: It was used the UN FAO’s Excel-based Bioenergy and Food Security (BEFS) Approach (Fig. 1). This approach developed by the United Nations Food and Agriculture Organization (FAO) is implemented through an Excel-based tool, which is designed to assess the interactions between bioenergy production, land use, water consumption and food security (FAO, 2022). The Excel-based tool incorporates various modules including: i) Crop module: This module estimates the potential availability of different crops for bioenergy production, considering factors such as yield, land availability, water availability and competition with food crops; ii) Land module: This module assesses the land use changes associated with bioenergy production, including the conversion of agricultural land to bioenergy crops and the potential displacement of food crops; iii) Food module: This module analyses the potential impacts of bioenergy production on food security indicators, such as food prices, household income, and access to food. It considers the trade-offs between bioenergy and food production and assesses the potential risks to vulnerable populations; iv) Wate module: This module shows potential impact of bioenergy production on water usage and contamination; v) Sustainability module: This module evaluates the environmental and social sustainability aspects of bioenergy production, including greenhouse gas emissions, and social equity considerations. In general, this approach offers a collection of simple-to-use approaches and tools to solve important issues regarding the potential of sustainable feedstocks, their techno-economic feasibility, and their socio-economic implications (Maltsoglou et al., 2015). The other benefits of the FAO's BEFS include global applicability, country-level evaluation, implementation in a short amount of time, use with limited data, provision of default values, and analysis that may be customized to meet the needs of individual nations.

Table III. Water availability in Kazakhstan, km^3 (UNDP, 2021)

River Basin	Internal water	External water	Total actual water	Total estimated groundwater reserves	Proven reserves
Aral-Syrdarya	3.36	18.93	22.29	9.29	1.13
Balkhash-Alakol	15.43	9.75	25.18	20.01	7.26
Irtysh	25.92	4.48	30.40	9.56	2.87
Ishim	2.77	0.00	2.77	2.31	0.16
Ural-Caspian	4.13	8.26	12.39	7.37	0.97
Nura-Sarysu	1.37	0.00	1.37	3.32	0.82
Tobol-Torgai	1.63	0.31	1.94	3.62	0.48
Chu-Talas-Assa	1.33	2.91	4.24	8.79	1.75
Total	**55.94**	**44.64**	**100.6**	**64.27**	**15.44**

Table IV. Water availability per capita in Kazakhstan, km^3 (UNDP, 2021)

River Basin	Internal water	External water	Total estimated groundwater reserves	Proven reserves	Total water resources
Aral-Syrdarya	6.68	1.00	2.92	0.36	7.02
Balkhash-Alakol	6.78	4.16	5.64	2.04	8.74
Irtysh	15.15	12.92	4.78	1.43	16.59
Ishim	1.34	1.34	1.17	0.08	1.42
Ural-Caspian	4.98	1.66	3.10	0.41	5.37
Nura-Sarysu	1.09	1.09	2.67	0.66	1.74
Tobol-Torgai	2.08	1.75	3.89	0.51	2.60
Chu-Talas-Assa	3.81	1.19	8.11	1.61	5.38
Average rate	5.95	3.31	3.93	0.94	6.86
Total	**16.30**	**9.06**	**10.76**	**2.57**	**18.79**

Table V. Water use in Kazakhstan, km^3 per year (UNDP, 2021)

Water withdrawal	
Total water withdrawal by sector	20.18 km^3 per year
- agriculture	14.76 km^3 per year
- public supply	0.87 km^3 per year
- industry	4.48 km^3 per year
- oil and gas sector	0.04 km^3 per year
- other	0.03 km^3 per year
- per inhabitant	1.32 km^3 per year
Surface water and groundwater withdrawal	19.98 km^3 per year

Mapping bioenergy potential: To visualize the most Kazakhstan's prospective regions in terms of the production of bioenergy as well as any potential limiting factors and hazards related to such production, the ArcGIS approach (Geographic Information Systems) was utilized. The ArcGIS provides a comprehensive set of tools and capabilities for spatial analysis, which is crucial for evaluating the suitability of different areas for bioenergy production (Ha et al., 2014). The ArcGIS tools use to perform spatial analysis and create suitability maps that identify areas with high potential for bioenergy production. This analysis involves factors such as land availability, soil quality, proximity to biomass sources, and infrastructure accessibility (Saha et al., 2015). Different weighted overlay techniques or multi-criteria analysis are employed to combine and prioritize these factors to generate suitability maps (Yang et al., 2022). The ArcGIS develops a few spatial models to simulate bioenergy production scenarios and their potential impacts. These models can consider factors including transportation logistics, supply chain optimization, or the spatial distribution of bioenergy facilities. The ArcGIS approach to the water-energy sector in the case of Kazakhstan was used for the first time, and due to some issues related to data availability, the output of ArcGIS utilization needs detailed explanation, e.g., through scenario analysis.

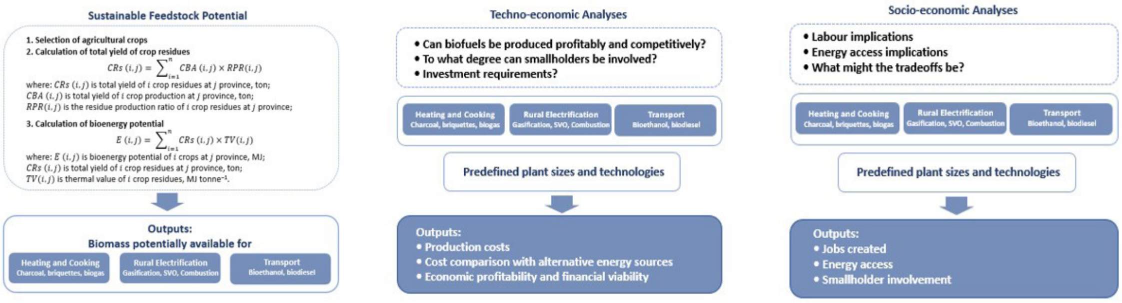

Figure 1. UN FAO’s BEFS Approach (FAO, 2022)

Scenario generation: It was used as an integrated nexus-based resource accounting tool for scenarios including future water withdrawal (Fig. 2). Using a multi-level geographic scale, this tool is used to investigate food, land, water, energy, and greenhouse gas emissions (Allwood et al., 2016). The integrated nexus-based resource accounting tool incorporates information such as: i) Resource data integration: The tool integrates relevant data from multiple sectors, including water, energy, and food systems. This data may include information on resource availability, consumption, infrastructure, and socio-economic factors; ii) Scenario modelling: The tool defines and simulates different scenarios to explore potential future developments, policies, and interventions. Scenarios include changes in resource demand, supply, technology adoption, or policy frameworks. Future scenarios are built around major change agents, including population, socioeconomics, and climate change; iii) Resource accounting and analysis: The tool performs accounting calculations to quantify the availability, use, and impacts of different resources. It analyses the interactions and trade-offs between sectors, identifying areas of resource stress or potential synergies; iv) Impact assessment: The tool assesses the potential impacts of different scenarios on resource availability, environmental sustainability, socio-economic indicators, and other relevant factors. It helps to identify potential risks, vulnerabilities, and opportunities associated with different resource management strategies; v) The visualization and reporting: The tool provides visualizations, maps, and reports to communicate the results of the analysis. This integrated tool includes the Sankey diagram method for visualizing the flow and linkages of all nexus components in the present and the future. These outputs help stakeholders understand the complex relationships and potential outcomes associated with different resource scenarios.

4. Preliminary results

Kazakhstan has abundant biomass resources available for bioenergy production. Crop residues, including wheat straw, maize stalks, and sunflower husks, are readily available from the country's agricultural sector. Forestry residues, such as wood chips and sawdust, can be sourced from the forestry industry. Additionally, energy crops like switchgrass, miscanthus, and willow can be cultivated for bioenergy purposes. Kazakhstan possesses the technical potential for various bioenergy technologies, including biomass combustion, biogas production, bioethanol, biodiesel production. These technologies potentially can be employed to convert biomass resources into heat, electricity, or biofuels. However, the adoption and implementation of these technologies may require appropriate infrastructure, investments, and technological expertise.

According to result of first stage of research (published in cooperation with Koshim et al., 2018), the bioenergy potential in Kazakhstan is estimated as 485.36 MJ based on net biomass yield from various residues and its conversion efficiency (thermal values of each type of residue) (or 16.582 million tons of coal equivalent, with an average of 14.150 Mt yr - 1). This equates to almost 30% of the nation's entire current energy consumption. In Kazakhstan, the largest source of biomass energy is wheat residue, which is grown mostly in the country's north (44%). The biomass energy potential from wheat residues is estimated to be 2846.3 Mt yr - 1 in other northern provinces (Fig. 3), 3101.4 Mt yr - 1 in Kostanay, and 3612.0 Mt yr - 1 in Akmola (Koshim et al., 2018). This shows the significant potential for using biomass co-firing technology in this region of Kazakhstan, with concurrent impacts on emissions leading to lower greenhouse gas release. Coal-fired power facilities are also common in these locations.

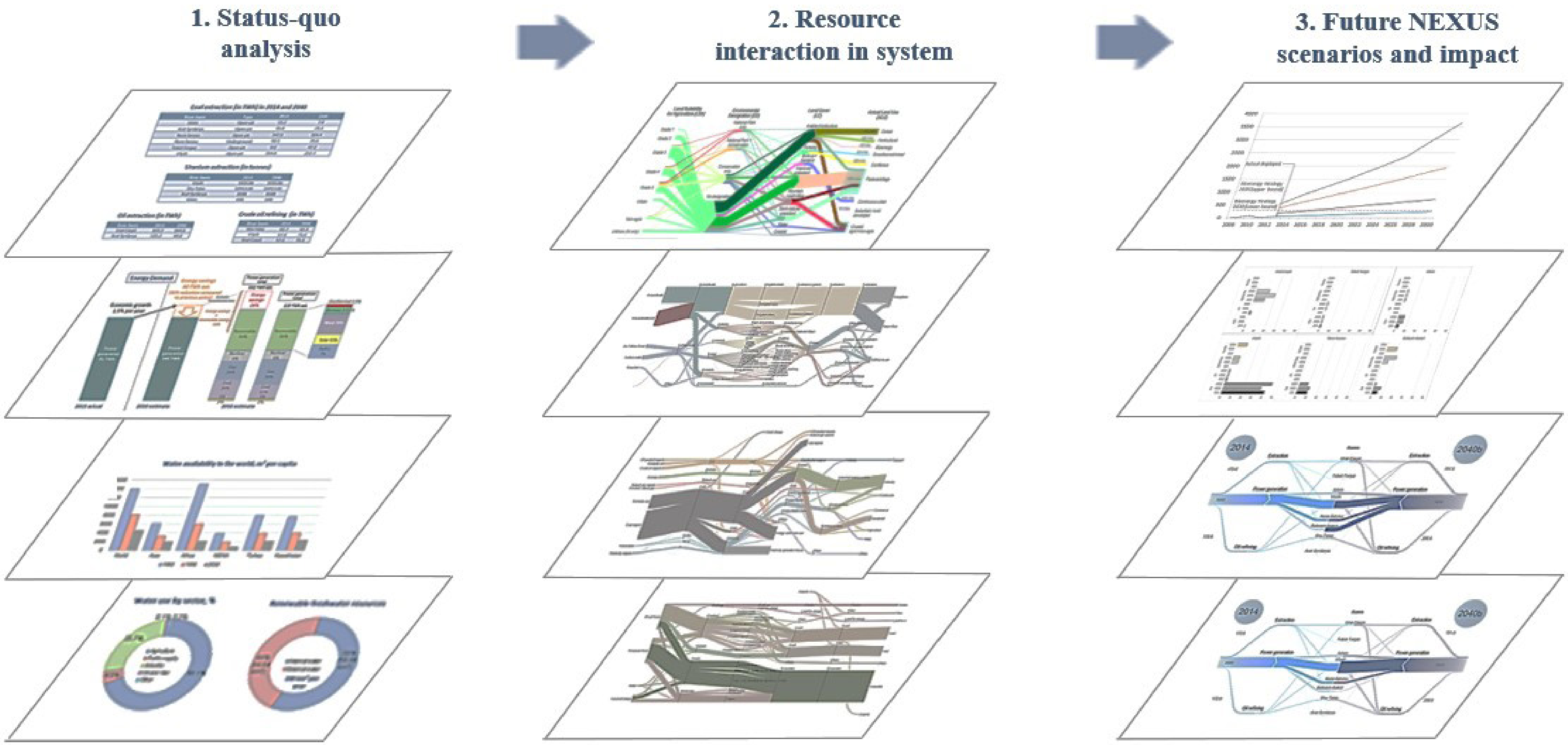

Figure 2. Framework for scenario generation (Karatayev, 2021, Rivotti et al., 2019)

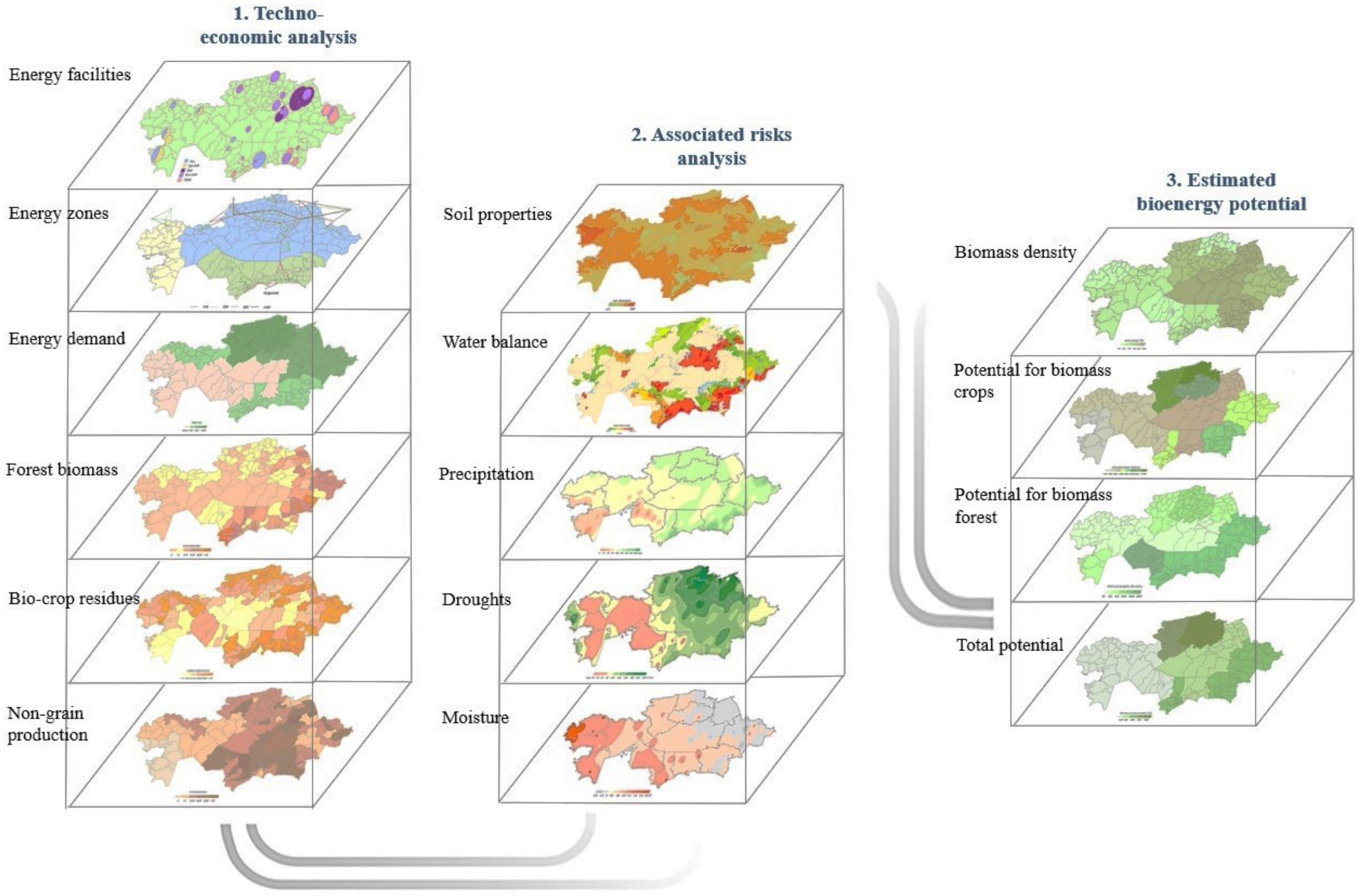

Figure 3. Country water-bioenergy-food potential, linkages & associated risks (Karatayev, 2021, Koshim et al., 2018)

The results showed that the main potential for the development of the biomass industry is in the northern provinces of Kazakhstan. Therefore, this research analysed the scenarios for the river basins located in the northern provinces. Another reason is that eight hydro-economic basins make up Kazakhstan's territory, namely the Aral-Syrdarya basin, the Balkhash-Alakol basin, the Irtysh basin, the Ural-Caspian basin, the Ishim basin, the Nura-Sarysu basin, the Shy-Talas basin, and the Tobol-Turgai basin. Within the country's territory, water resources are dispersed unevenly and exhibit considerable seasonal and perennial variations. For example, only 3% of the country's total water resources are in the river basins of the Tobol-Torgai and Nura-Sarysu. On other hand, the Irtysh and Balkhash-Alakol river basins produce over 75% of the country's water resources.

There are three possible outcomes: Scenario A, which represents current agriculture-energy development trends; Scenario B, which includes integration of low bioenergy ambitions at 10-15% to agriculture, and Scenario C, which includes more ambitious bioenergy targets of up to 25-30% into agriculture. Future water withdrawal scenarios are based on current trends for crucial driving forces and projections of how those trends will alter in the future. The crucial driving forces are population growth, economic development, technological change, and expectations regarding changes in land-use and irrigated areas. It is assumed that if no limits are put in place by legislation and policy restrictions, irrigation is expected to be crucial in delivering feedstock for bioenergy.

Table VI. Total water withdrawal scenarios, m^3

Scenarios	1990	2012	2015	2020	2030	2040	2050
Baseline scenario	27040.37	12349.95	14761.23	15503.68	18179.47	20144.61	24755.51
Low bioenergy targets	NPD	NPD	NPD	NPD	20724.59	22964.85	28221.28
More bioenergy intensive	NPD	NPD	NPD	NPD	23633.31	26187.99	32182.16

**NPD: non-predicted data*

This paper offers perceptions into the effects of large-scale bioenergy production on water resources, but it makes no promise to provide a complete picture of future bioenergy-related water resource requirements under various scenarios. The scenarios for future water withdrawal are summarized in Table VI. By 24755.51 m^3 (or average 42.6%) in 2050, total water withdrawals under the baseline scenario rise from their actual amount of 15503.68 m^3 in 2020. Total water withdrawals would rise by 28221.28 m^3, or average 59.9%, under the scenario's assumptions of low bioenergy targets. Total water withdrawals increase from the reported data of 15503.68 m^3 in 2020 to 32182.16 m^3 in 2050 under a more bioenergy-intensive scenario. The average total increase, or 75.5%, would be 16678.48 m^3. These findings are consistent with studies demonstrating how water is used extensively in the bioenergy sector (Bonsch et al., 2016). As a result, Kazakhstan needs to carefully design its national bioenergy goals given its water shortage environment.

5. Conclusion

Using the case of Kazakhstan, this paper shows five main points to take away. First, Kazakhstan's total water requirements keep rising with population growth, economic expansion, agriculture, and energy policy development. Nevertheless, whether assumptions and estimates about future conditions would prevail, the change in the overall water demand could be more remarkable or slower. Second, the results show a mismatch between energy policy and the actual physical constraints of natural resources. Kazakhstan is rich in fossil fuel resources, including oil, gas, and coal. Extracting and processing these resources requires substantial amounts of water, which can strain already limited water supplies. Furthermore, the water used in extraction processes is become contaminated, posing environmental risks, and impacting water quality for other users. Additionally, the production and processing of bioenergy, particularly biofuels and biomass-based power generation requires significant amounts of water. These water requirements need to be carefully managed, especially in region where water scarcity is a concern. Third, making the water-energy-agriculture targets more achievable and quantitatively measurable is essential. Thus, key actors are motivated to accomplish the targets, and their contributions are evaluated. Quantitatively measurable targets allow for the monitoring and tracking of progress over time. Regular monitoring enables the identification of gaps, successes, and areas that require adjustments or additional efforts. It helps assess the effectiveness of policies and interventions, allowing for evidence-based decision-making and accountability, optimizing resource allocation, attracting investments, and facilitating international comparisons. Fourth, there is a lack of information and awareness of the dynamics of the relationship between agriculture, energy, and water, as well as the analysis of potential trade-offs. In fact, agriculture is a crucial sector in Kazakhstan, contributing significantly to food production and rural livelihoods. However, agricultural irrigation is a major consumer of water resources in the country. Increased water demands for irrigation, coupled with energy-related water needs, can exacerbate the competition for water resources and strain the overall water availability. Finally, to better and more effectively support science-based policy formulation and implementation processes, Central Asian region and

Kazakhstan must encourage integrated nexus modelling research and the creation of nexus knowledge. It helps identify policy options and interventions that can optimize resource use, minimize trade-offs, and maximize co-benefits across sectors.

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