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Optimal paths for electricity interconnections between Central Asia and Europe

A methodology integrating the potential of renewable energy in the crossed countries

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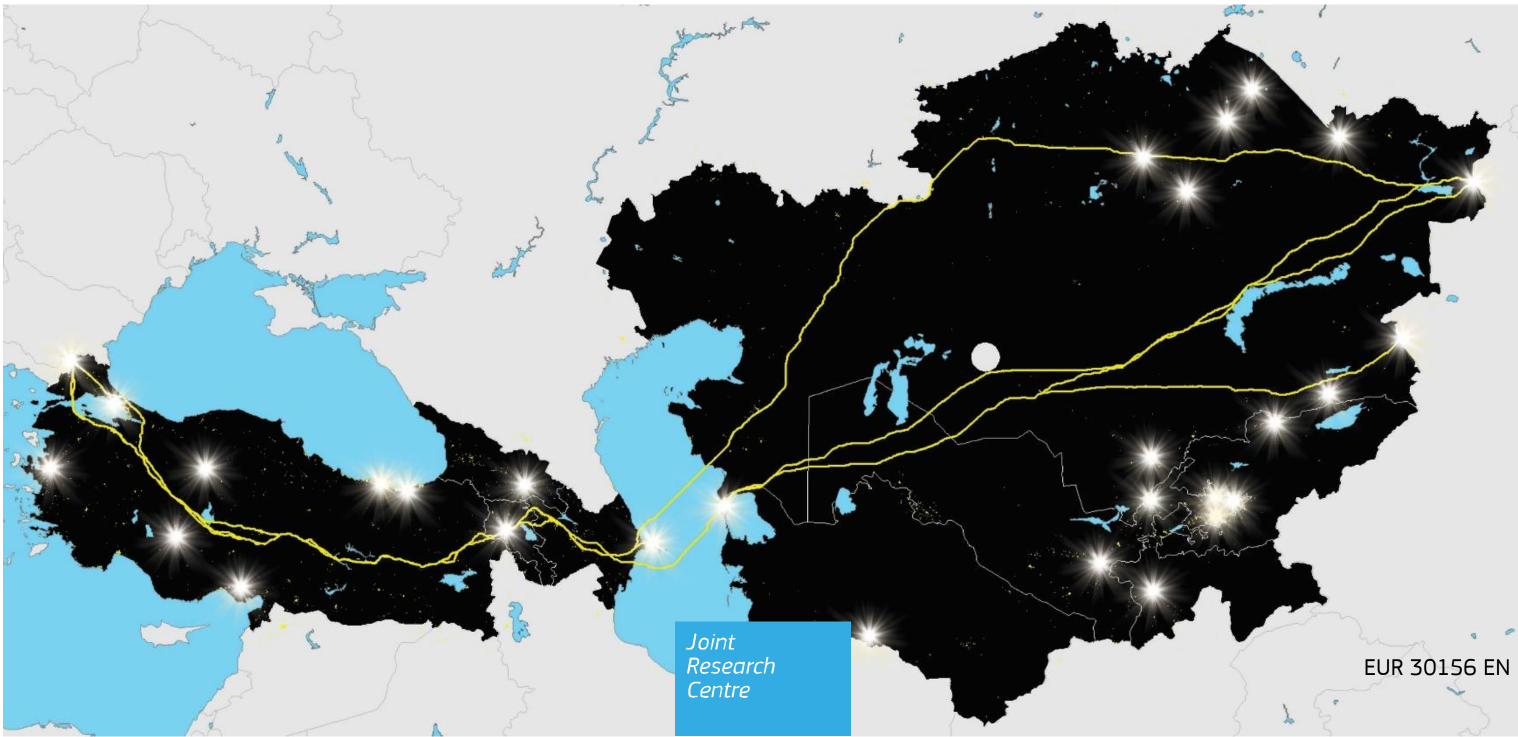

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Contents

Abstract

The European Union is increasingly considering energy cooperation with Central Asia as this is a relatively nearby and stable region with tremendous energy resources. Locally produced electricity – i.e. predominantly from gas and hydro and potentially from solar and wind energy – offer opportunities for beneficial electricity trade, both among the Central Asian countries and with the European Union. As such, Central Asia may contribute to the European Union's security of electricity supply and the achievement of its renewable energy targets. Underpinning policies and strategies for improved energy connectivity with Central Asia and the use of renewable energy sources in this region have been developed. However, efficient electricity interconnections are still lacking, hindering the full potential of Central Asia's energy resources. Against this background, this report presents a methodology for the computation of optimal electricity transmission routes, crossing Central Asia, the Caspian Sea and the Transcaucasia towards the European Union. This methodology, which is based on the concept of cost (friction) maps, makes use of a set of 13 input variables and is implemented in geographic information system software. For each pixel of the cost map, covering the addressed countries, a crossing cost is calculated from semi-quantitative friction scores, which are locally attributed to the variables. Starting from the final cost surface, which represents a composite weighted map of the constituent variables, the software model successfully evaluates the least-cost paths for electricity transmission throughout the considered region. It is found that the evaluated route is most sensitive to the renewable energy potential across the considered region and not to the already existing electricity assets.

Executive summary

Context

International electricity interconnections offer opportunities for beneficial electricity trade between the interconnected countries, at the same time enhancing security of supply and supporting integration of renewable energy sources (RES) in these countries. Within the European Union (EU) the impact of electricity interconnections between Member States (MS) has been fully acknowledged as well-interconnected and integrated European grids are indispensable for making the energy transition a success. In addition, the European Commission (EC) considers interconnections with third countries, as far as they enhance security of supply and help to increase electricity consumption from RES. In this context, Central Asia is increasingly considered as an appealing region for energy cooperation as it is a relatively nearby and stable region with tremendous potential for electricity production, given the available gas, water and uranium resources. Moreover, opportunities for electricity generation from wind and solar energy are increasingly apparent in the Central Asian region. Hence, Central Asia offers potential for the EU in terms of security of electricity supply and electricity imports from renewable energy, i.e. hydro, solar and wind. Where electricity imports require efficient transmission interconnections, the Central Asian countries are still among the least connected in the world. Along with initiatives from other world powers – most importantly the Chinese Belt and Road Initiative (BRI) – this connectivity issue is addressed by dedicated EU strategies. In line with this, the current report explores the most optimal routes for electricity transmission interconnections between Central Asia and the EU. For this purpose, a semi-quantitative methodology based on friction maps has been developed.

Policy framework

Beneficial electricity imports from Central Asia to the EU require underpinning policies and strategies. From the EU side MS are allowed to cooperate with third countries with regard to the production of electricity from renewables. Electricity from RES produced in a third country is taken into account for calculating the renewable energy shares of the MS. In addition, the EU has initiated dedicated strategies for cooperation with Central Asia. These strategies point at the significant energy resources in the Central Asian region, which can help the EU in meeting its energy security and supply needs. Moreover, the region's potential in solar, wind and hydroelectric energy is highlighted. The EU aims at facilitating electricity interconnections on a level playing field, both in and with Central Asia. EU energy diplomacy efforts should play a pivotal role in the required process towards improved energy collaboration with and among the Central Asian states. In Central Asia, there is a general lack of coherent policies on energy cooperation with neighbouring countries and other regions as the Central Asian countries have traditionally opted for energy self-sufficiency. Nevertheless, the Central Asian countries are increasingly recognising the benefits of regional cooperation from the viewpoint of economic benefits. In addition, there is a rising awareness among these countries regarding the impact of climate change and environmental pollution. A variety of policies and laws on renewables has been developed, also offering increased opportunities for the EU for importing electricity from RES from Central Asia.

Electricity generation and transmission in Central Asia

Energy resources are unevenly distributed within Central Asia. The main quantities of electricity produced in Kazakhstan, Turkmenistan and Uzbekistan come from fossil fuels, which are locally exploited. Tajikistan and Kyrgyzstan are mountainous countries with high hydropower potential, which is reflected in the share of electricity generated by hydropower plants (more than 90%). Central Asia owns large reserves of uranium with Kazakhstan and Uzbekistan being among the top producers in the world. Nevertheless, there are currently no nuclear power plants in operation in the region.

The potential of solar energy in Central Asia is generally high, decreasing from south to north. Local variances are found, especially in the mountainous areas of Kyrgyzstan and Tajikistan. Wind potential is moderate, displaying higher opportunities along the mountainous ridges in southern Kazakhstan and across the open steppes in the east of Caspian Sea. However, current electricity production from solar and wind energy is very limited in Central Asia. During the Soviet era, the five Central Asian republics were interconnected through the Central Asian Power System (CAPS). After independence, some of them disconnected from the system jeopardising security of electricity supply in the region, especially in the countries relying on hydropower. However, new initiatives are observed to reconnect countries, reinitialising beneficial electricity trade in the region. Most of current Central Asian electricity assets originate from the 1970s and are in an outdated state. Distribution and transmission losses together are close to 20%. This situation severely affects power supply and requires large investments. The actual configuration of the Central Asian transmission grids is complex, as it is heavily influenced both by geographical factors and its Soviet legacy.

Methodology

To each point (pixel) on the geographic map of Central Asia, the Transcaucasia and Turkey a crossing cost is attributed, which acts as a friction surface. Accordingly, a friction map is created that is used for computing optimal routes, which follow the "cheapest" path between defined start and end points. The total cost associated with a pixel is evaluated from semi-quantitative values – friction scores – attributed to the utilised variables. These variables are grouped in five categories: terrain parameters (elevation and slope), land use factors (land cover and protected areas), RES potential (solar, wind and hydro), natural and man-induced hazards (earthquakes, landslides, soil erosion, floods and armed conflicts) and proximity to power infrastructure. The five categories of variables are weighted with respect to their composite friction score. In addition, the individual variables are weighted inside their own categories. As such, the final cost surface represents a composite weighted map of the constituent variables. Evaluation of least-cost paths is a common process that can be performed by most geographic information system (GIS) software. However, building the cost surface on which the computation is executed remains the user's responsibility.

The model and scenario results

The model used for the analysis is built by means of the application *ModelBuilder*, which is included in the ArcGIS 10.1 software. Input data consist of the defined variables, harmonized regarding their spatial parameters (i.e. resolution, projection, origin and spatial extent). Five functions are used throughout the modelling: Reclassify, Weighted Sum, Cost Distance, Cost Path and Raster to Polyline. These functions are assembled into a unitary model (except Reclassify), which can be run either function by function, or of one shot, making the operation more efficient.

A number of assumptions is made, i.e. regarding the nature of the factors influencing the route, the classes of scores associated with the variables and the weighting of the variable categories. The departure point and the end point of the routes are fixed, i.e. at the easternmost extremity of Kazakhstan and the three country's border of Turkey, Bulgaria and Greece, respectively. For crossing the Caspian Sea, two anchor points are fixed for the end stations of the required submarine power cable.

Three scenarios are modelled. In the base scenario, all variables contribute to assembling the final cost surface. The no-renewables scenario excludes RES potential from the evaluation of the final cost map. The influence of existing infrastructure is ignored in the no-substation scenario. The shortest route is found for the base scenario. The cost maps of the base and no-substation scenarios are very similar and so are the resulting optimal paths. When RES potential is excluded (second scenario), the optimal path deviates considerably and becomes significantly longer, indicating the determining impact of the solar, wind and hydro variables in the analysis.

Conclusions

A semi-quantitative methodology, based on friction maps, is developed for the assessment of optimal routes for electricity transmission between Central Asia and Europe. A variety of weighted variables is used for building a cost surface covering the considered countries, which is input to a GIS software model. The model successfully computes the routes under three different scenarios. It is found that the evaluated route is most sensitive to the RES potential across the considered region and not to the already existing electricity infrastructure, which is represented by current substations.

1 Introduction

The socio-economic value of international electricity interconnections arises from their intrinsic ability to enhance the performance of electricity systems and markets in various ways. These interconnections have the capacity to couple national electricity markets, as such fostering beneficial electricity trade with potential economic surpluses for consumers, producers and merchants in the interconnected countries. This obviously requires alignment of the electricity market rules of these countries. Accordingly, the interlinked nations may profit from enhanced security of supply, provided that the interconnections are made with reliable and stable energy partners.

Moreover, these interconnections play an important supporting role related to the growing share of intermittent renewable energy sources (RES) in the electricity generation mix, most importantly for power balancing purposes. Optimisation of the balancing process, which is a genuine alternative for energy storage, requires the involvement of several countries with a variety of RES producing electricity at complementary times. Finally, investment in interconnections offer, as a positive spill over, opportunities for the development of innovative technologies and related employment (European Commission, 2019).

Within the European Union (EU) the European Commission (EC) recognises the importance of electricity interconnections between Member States (MS) as well-interconnected and integrated European grids are indispensable for making the energy transition a success (European Commission, 2017). Selected cross-border projects have been granted the status of Project of Common Interest (PCI), with the aim to boost the related investments and limit financing costs (EURACTIV Network, 2018). In addition, the EC looks into the potential of interconnections with third countries, herewith promoting the external policy objectives of the EU. Apart from economic cooperation, socio-economic welfare, and peace and solidarity, these objectives also encompass energy-related aspects, like integration of renewables and security of supply. Hence, interconnections should be promoted that significantly enhance security of supply and help to increase electricity consumption from RES, both in the EU and in the third countries, with the overall objective of intensifying the energy transition towards the decarbonisation goals in and outside the EU (European Commission, 2019).

Beyond the Western Balkans, Ukraine and Moldova also Central Asia is increasingly considered as an appealing region for energy cooperation. This region, consisting of Kazakhstan, Turkmenistan, Uzbekistan, Kyrgyzstan and Tajikistan, has evolved into a relatively stable region in spite of some short-term, small-scale conflicts (Geopolitical Monitor, 2018). Most importantly, it has tremendous potential for electricity generation, given the available gas, water and uranium resources (Asian Development Bank, 2010). In addition, various study programmes have revealed substantial opportunities for electricity generation from wind and solar energy (Eshchanov, Wind Power Potential of the Central Asian Countries, 2019) (Eshchanov, Solar Power Potential of the Central Asian Countries, 2019). Hence, Central Asia incorporates intrinsic opportunities in terms of security of supply and deployment of RES, both for itself and for other regions, including the EU. Efficient electricity transmission interconnections are a prerequisite to exploit this potential.

However, the Central Asian countries are still among the least connected, both internally and with the rest of the world. Regrettably, this fully applies for electricity transmission interconnections. At the background are not only geographical barriers (including high mountains and harsh climates) but also historical aspects (the Soviet legacy) and political factors (the isolationist characteristics of current regimes). Nevertheless, the major world powers have launched various initiatives challenging the isolation of Central Asia. For example, in 2011 the United States (US) initiated the “New Silk Route”, a project aiming at linking Central and South Asia in four areas, including regional energy markets. However, this initiative never got off the ground.

Since 2015, Russia is one of the driving powers behind the Eurasian Economic Union (EAEU). However, this organisation is mainly focussing on customs issues (a “limited customs union”). Most importantly, in 2013 China launched its “Belt and Road Initiative” (BRI). This worldwide initiative addresses Central Asia in the context of a booming EU-China trade. China has a policy to invest in strategic infrastructural assets along the two “belts” crossing Central Asia, including electricity generation and transmission assets (European Parliament, 2019). During the last decade also, the EU has been developing strategies to intensify connectivity with and among the five Central Asian countries, e.g. as part of the overall “Strategy for Connecting Europe and Asia”. Energy connectivity is an important aspect in these strategies (European Commission, 2018).

Against the above considerations, it is justified to carry out dedicated scientific studies exploring the most optimal routes for electricity transmission interconnections (lines and cables), both in Central Asia and between Central Asia and other regions. The current report addresses potential routes between Central Asia and Europe, crossing the Caspian Sea and the Transcaucasia. Through cross-border electricity trade, these routes could serve the EU in terms of security of electricity supply as well as for achieving its renewable energy targets. Evaluated routes may diverge from existing transmission tracks depending on the variety of affecting factors used in the analyses.

Aspects that can be considered include the proximity of already existing electricity assets (e.g. substations), as well as geographical factors, like mountains and seas. Other factors that can be taken into consideration are land use types, and natural and man-induced hazards. The methodology presented in the current report has the unique capacity to also include the potential of unexploited RES across the traversed areas in the modelling of the optimal routes. Where past investigations have used rather qualitative approaches for evaluating electricity interconnections crossing Central Asia (Ardelean & Minnebo, 2017), this report presents a systematic semi-quantitative methodology based on cost maps.

2 Underlying policies

The relevance of the presented study is underpinned by a set of energy-related policies and strategies, both on interconnections and on renewables, predominantly from the EU side. The "EU Directive on the Promotion of the Use of Energy from Renewable Sources" stipulates that the MS shall collectively ensure that the share of energy from renewable sources in the Union's gross final consumption of energy in 2030 is at least 32%. Article 11 of this directive states that MS may cooperate with one or more third countries on all types of joint projects with regard to the production of electricity from renewable sources. Electricity from RES produced in a third country is taken into account for calculating the renewable energy shares of the MS if a number of specified conditions are met (European Parliament and Council, 2018). Electricity imports from Central Asia can be beneficial for the EU in this context, given the massive availability of hydropower resources and the additional potential of wind and solar energy in the region. In addition, there are well-established EU strategies for connectivity with Central Asia.

The "Strategy for a New Partnership between the EU and Central Asia", which was launched in 2007, points – once again – at the significant energy resources in the Central Asian region, which can help the EU in meeting its energy security and supply needs (Council of the European Union, 2007). In its conclusions of 2015 and 2017 on this strategy the Council indicates that the EU will continue to promote renewable energy in Central Asia by offering its expertise in the development of sound regulatory frameworks and by supporting investment cooperation with European financial institutions (Council of the European Union, 2015) (Council of the European Union, 2017).

Recent developments in Central Asia have triggered a "New Strategy" for this region, preceded by a Joint Communication of the EC and the EU High Representative (HR) for Foreign Affairs and Security Policy: "The EU and Central Asia: New Opportunities for a Stronger Partnership". This communication reaffirms the importance of Central Asia for the EU in terms of energy imports, market potential, as well as regional security and stability. Under the "Partnering for Resilience" priority, the EC and the EU HR highlight the region's potential in solar, wind and hydroelectric energy and propose the EU to foster reforms in the Central Asian energy sector as well as transition towards a low-carbon economy.

The "Partnering for Prosperity" priority calls for promoting sustainable connectivity enhancing the role of Central Asia in contributing to the EU security of energy supply, i.e. through diversification of suppliers, sources and routes (European Commission, 2019). In its "Conclusions on the New Strategy on Central Asia" the Council agrees that the EU should step up cooperation with the countries of this region on renewable energy and energy efficiency, as well as facilitating electricity interconnections on a level playing field (Council of the European Union, 2019). The latter is fully in line with the "EU Strategy for Connecting Europe and Asia". This strategy was initiated through a Joint Communication of the EC and the EU HR: "Connecting Europe and Asia - Building Blocks for an EU Strategy".

Regarding energy connectivity this communication states that through its own experience the EU should promote Central Asian connectivity platforms that focus on market principles. Moreover, the EU should support energy connectivity both between and with partners in Asia (European Commission, 2018). In its conclusions on this communication the Council highlights the need to address the ongoing market-driven transformation towards renewable energy, which demands for electricity interconnections and thus regional cooperation in Europe and Asia. The Council also calls for better-integrated energy markets and further harmonisation of regulatory frameworks with non-EU countries, while preserving energy security (Council of the European Union, 2018). EU energy diplomacy efforts can play a pivotal role in the required process towards improved collaboration with the Central Asian states, given its role in the area of energy cooperation with third countries. The "EU Energy Diplomacy Action Plan" is instrumental in this context (Council of the European Union, 2015).

In Central Asia there is a general lack of coherent policies related to energy cooperation with neighbouring countries and other regions. In terms of security of supply the Central Asian countries have traditionally opted for energy self-sufficiency, which is in line with the established isolationist policies of these nations, characterised by a high degree of mutual mistrust. However, Central Asian countries are increasingly recognising the benefits of regional cooperation from the viewpoint of economic opportunities, i.e. beneficial trading. For example, several countries are participating in the Central Asia Regional Economic Cooperation (CAREC) Programme, which aims at stronger integration of energy markets and consequent economic growth through energy trade (Energy Charter, 2015). In addition, there is a rising awareness among the Central Asian countries regarding the impact of climate change and environmental pollution. Especially the role of the power sector in this field is considered and policies and laws on renewables have been developed, offering increased opportunities for the EU for importing electricity from RES from Central Asia (Eshchanov, Renewable Energy Policies of the Central Asian Countries, 2019).

In Kazakhstan, where electricity is mainly produced in coal-fired power plants, ambitious targets have been set for the share of alternative energy in the power generation mix (rising from close to 1% today, to 30% by 2030 and 50% by 2050) (Republic of Kazakhstan, 2013). In fact, the "Law on Support of Use of Renewable Energy Resources" is still the basic driver for concrete actions on the deployment of RES (Republic of Kazakhstan, 2009). This law, which fosters the production of electricity (and heat) from RES through a set of incentivising measures, has been amended several times, with a main revision in July 2013.

In Uzbekistan, natural gas-fired thermal power plants are the main source of electricity, supplying over 85% of the country's total power. Anticipating to the apparent opportunities offered by RES the President of Uzbekistan signed in 2017 a resolution "On the Programme of Measures for Further Development of Renewable Energy, Improving Energy Efficiency in Economic and Social Spheres for 2017-2021". This resolution includes targets for the further development of renewable energy, envisaging an increase of the share of RES in generating capacities to 19.7% by 2025. This involves hydropower (15.8%), solar energy (2.3%) and also wind energy (1.6%) (Republic of Uzbekistan, 2017). Moreover, the Senate of the Republic of Uzbekistan approved the "Law on Using of Renewable Energy Resources" in May 2019. This law grants tax-related benefits to producers of electricity from RES (Senate of Uzbekistan, 2019).

As Tajikistan has abundant water resources, hydropower is obviously the main source of electricity in the country (over 95%). However, its theoretical potential is only used for less than 5% (Eshchanov, et al., 2019). Nevertheless, within the "Sustainable Energy for All" framework Tajikistan introduced a target of a 20% increase of electricity production from RES by 2030 (United Nations, 2013). Actually, additional hydropower and supplementary RES (solar and wind) in Tajikistan offer opportunities for mitigating the frequent electricity shortages in the country (Eshchanov, Solar Power Potential of the Central Asian Countries, 2019) (Eshchanov, Wind Power Potential of the Central Asian Countries, 2019) (Eshchanov, et al., 2019). In addition, the "Law on the Use of Renewable Energy Sources" of 2010 regulates the activities in the field of RES, including the principles and objectives of policies in the field of renewable energy. It identifies ways of integrating RES in the power system as well as organisational, research, engineering and regulatory activities aimed at increasing the use of RES (Republic of Tajikistan, 2010).

As is the case for Tajikistan, also Kyrgyzstan's energy mix is highly dependent on hydropower (almost for 90%), which makes generation sensitive to seasonal weather variations. In 2008 Kyrgyzstan was the first country in Central Asia that adopted a so-called "Renewable Energy framework Law", which presented the general principles for the regulation of RES. The "National Programme on Sustainable Development for 2013-2017" sets a target of 1.5% (beyond hydropower) for the share of renewable energy in total energy consumption by 2017 and stipulates a number of measures to facilitate the achievement of this target (Government of Kyrgyzstan, 2013).

Turkmenistan owns the fourth largest total offshore and onshore gas reserves in the world. Accordingly, natural gas accounts for nearly 100% of the country's current power mix. Nevertheless, the government of Turkmenistan is increasingly aware of the importance of climate change. This is apparent from official documents and initiatives, such as the "National Climate Change Strategy", which mainly focuses on adaptation measures, especially in the water and agriculture sectors (United Nations, 2013). However, climate-related policy developments lack a solid legislative basis because of insufficient coordination and harmonisation among legislative documents as well as the lack of effective implementation and enforcement of policies and programmes (World Bank, 2013). For example, Turkmenistan is the only country in Central Asia without precise targets for renewable energy capacity expansion not to speak of renewable energy regulatory policies and fiscal incentives (Eshchanov, Renewable Energy Policies of the Central Asian Countries, 2019).

3 Energy sources and infrastructure[1]

3.1 Fossil thermal (coal, oil, gas)

The largest part of the electricity produced in the Central Asian countries comes from the use of fossil fuels exploited in the region. The fuel used to generate electricity generally reflects the locally available resources. Kazakhstan holds large coal reserves, which makes that more than ¾ of its electricity to be generated in coal-fired power plants. Both Turkmenistan and Uzbekistan own significant gas reserves, with 99% and more than 80% of their respective electricity being generated by gas-fired power plants. Tajikistan and Kyrgyzstan, however, are mountainous with high hydropower potential, which is reflected in the share of electricity generated in hydro power plants: 97% and 90% respectively (EIA, 2019) (UN Data, 2019).

Countries that run their power systems on fossil fuel seem to better cover their demand and experience less blackouts and scheduled interruptions. The seasonal character of hydropower makes it hard for the concerned countries to maintain a steady and thorough supply of electricity. This is mostly valid since the dismantling of the Central Asian Power System (CAPS), which was built during the Soviet Union times for the complementary use of the energy resources available in Central Asia (Mercados, 2010).

In 2016 (i.e. the latest most complete available dataset), the five countries of Central Asia possessed together an installed capacity of 53152 MW (**Table 1**) and produced 208 TWh (**Table 2**) of electricity, split as follows:

Table 1 - Installed capacity (MW) in 2016

	Fossil fuels	Hydro	Wind	Solar	Total
Kazakhstan	22 500	2 500	170	53	25 223
Kyrgyzstan	801	3 064	-	-	3 865
Tajikistan	719	5 858	-	-	6 577
Turkmenistan	4 674	-	-	-	4 674
Uzbekistan	10 958	1 855	-	-	12 813
Total	39 652	13 277	170	53	53 152

Source: (UN Data, 2019)

Table 2 - Electricity generation (TWh) in 2016

	Fossil fuels	Hydro	Non-hydro renewables	Total
Kazakhstan	89	12	0.4	101
Kyrgyzstan	1.7	11	-	13
Tajikistan	0.6	16	-	17
Turkmenistan	21	-	-	21
Uzbekistan	44	12	-	56
Total	156.3	51	0.4	207.7

Source: (EIA, 2019)

Most of the power plants in the region were built 50 to 60 years ago and did not undergo technological updates apart from regular maintenance, which affects their efficiency and environmental performance

[1] The facts and figures in Chapter 3 are compiled (unless otherwise mentioned) from various online sources, including press releases, statistics and analysis. Some of the sources used: adb.org; ft.com; hydropower.org; reuters.com; tradingeconomics.com; uzdaily.uz; worldbank.org; world-nuclear-news.org.

(World Energy Council, 2007). Only a handful of old power plants underwent renovation works. The newest capacities put online or built exploit renewable resources: mainly hydro and also wind and solar lately, although the last two still at very modest scales.

Obviously, the distribution of the power plants follows the “fluidity” of their fuel. The hard-to-transport fuels, like coal, or the place-bound resources, like hydro, decided the location of the corresponding power plants, i.e. – nearby the deposits or high-potential sites. The easily transportable fuels, like gas and oil, offered more flexibility and allowed the power plants to be built closer to the demand centres. In fact, many towns and industries in the region grew around the first-used fossil resources. As such, the coal-fired power plants dominate the north of Central Asia (northern Kazakhstan) while the hydropower plants are dominant in the southeast (Tajikistan and Kyrgyzstan). Mainly gas-fired power plants cover the west, as well as the south. They dot the path of few major gas pipelines originating mainly in Turkmenistan and heading northward. They are also present in areas with larger population and industry, displaying a high demand.

3.2 Nuclear

Currently, there are no electricity-producing nuclear reactors in the Central Asian countries. In the realm analysed only Armenia has one nuclear reactor of 375 MW. It covers 25% of the total electricity generation in the country. Kazakhstan had one nuclear reactor running between 1972 and 1999, however with the main purpose of desalinating water.

Lately, Uzbekistan considers nuclear energy as an option for the near future. Plans include building four nuclear reactors with Russian support. The first two units (VVER-1200 type), scheduled to go online in 2028 and 2030, would have a capacity of 1200 MW each and would produce 21 TWh of electricity per wear by 2030, covering 18% of the country’s total generation. The site for these units is planned close to water resources and not far away from the country’s largest uranium mine at Navoi.

Although Kazakhstan also had discussions with Russia on the opportunity of building a nuclear power plant (two or three reactors), no concrete plans have been publicly announced.

Throughout the region, there are still legacies of a more active and inclusive nuclear fuel processing, including for nuclear weapons. In all countries of Central Asia, there were facilities – some still operating – covering the different technological steps of the processing procedures.

Though Central Asia does not have any nuclear power plants for producing electricity, the region has vast reserves of nuclear fuel – uranium - with Kazakhstan and Uzbekistan being among the top producers in the world. Kazakhstan and Uzbekistan hold respectively 14% and 2% of the world’s uranium resources.

Kazakhstan has four of the top ten most productive uranium mines in the world, with only these covering 16% of the world’s output. The country covers in total 41% (in 2018) of the world supply (World Nuclear Association, 2019). The country will continue to keep the same level of production for the years to come. Also, other countries in Central Asia (Kyrgyzstan, Tajikistan and Turkmenistan) have some uranium reserves but more modest than Kazakhstan and Uzbekistan and their production is small. The region will continue to be one of the main suppliers of nuclear fuel with the aim of diversifying and providing value-added fuel. In this respect, Kazakhstan is building a fuel fabrication plant with Chinese assistance. The fuel material is exported outside the region.

3.3 Renewable energy sources potential in Central Asia

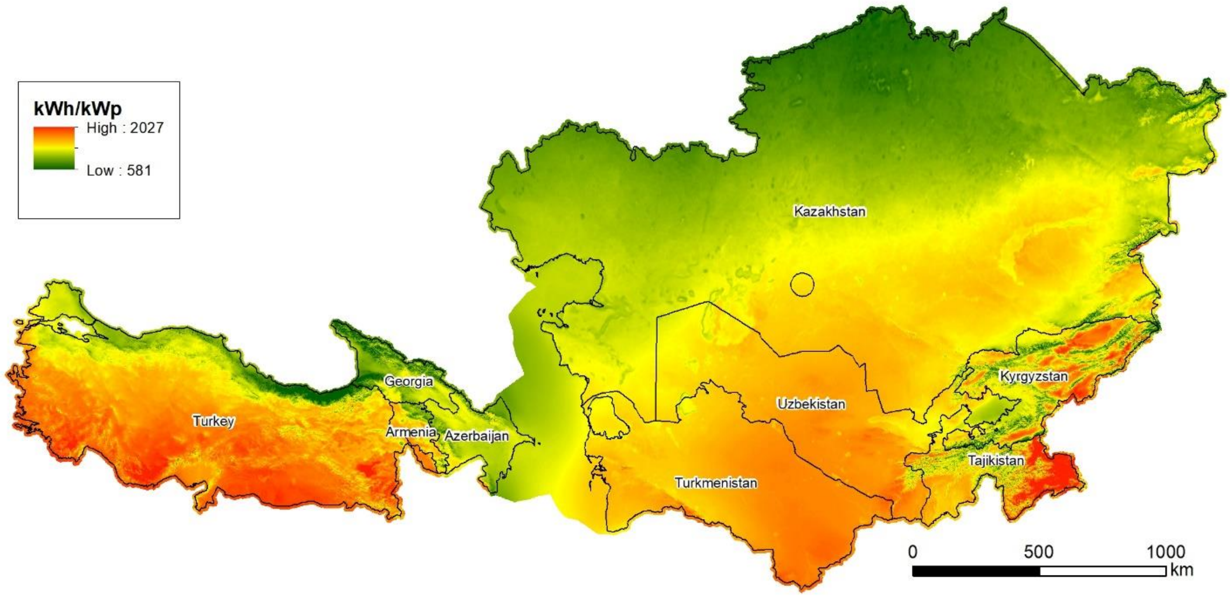
The Central Asian region offers large potential for electricity production from RES: mainly solar and hydro (the latter being strongly localised) and also wind (moderate by capacity factor, but high by the broad area covered). However, more than 75% of the produced electricity still comes from fossil fuels. Underlying causes include the abundance of the inexpensive and heavily subsidised fossil fuels, the risky investment conditions and the lack of energy cooperation in the region. Nevertheless, all Central Asian countries (apart from Turkmenistan) are increasingly initiating policies (e.g. tax exemptions) to promote the deployment of RES on their territory.

For the analyses presented in current report the potential of RES is mapped in the Central Asian countries as well as in the Southern Caucasus and Turkey, which are crossed by the envisaged electricity interconnections towards Europe.

3.3.1 Solar potential

The solar potential of Central Asia is significant, displaying higher values than the average Euro-Asian continental mass, but lower values than the tropical and subtropical deserts located further south. Transcaucasia shows smaller potential (**Figure 1**).

Figure 1 – The solar potential in the Central Asia study area



Source: (Solargis s.r.o. on behalf of the World Bank Group, 2019)

Solar energy has the advantage of being predictable and relatively constant but has also the disadvantage of generating electricity only during daytime (when the sun shines) and possibly when local electricity demand is low. Solar energy achieves its full usefulness when the generated electricity can be transmitted to areas located in other time zones, which are in a high demand window of their consumption profile.

The solar potential in Central Asia decreases from south to north. The relief and other local factors introduce variations of this disposal by creating anomalies. Such anomalies are especially found in the mountainous areas of Kyrgyzstan and Tajikistan, where, depending on the air masses influence with different humidity, the solar potential suffers from deviations from the latitudinal gradient.

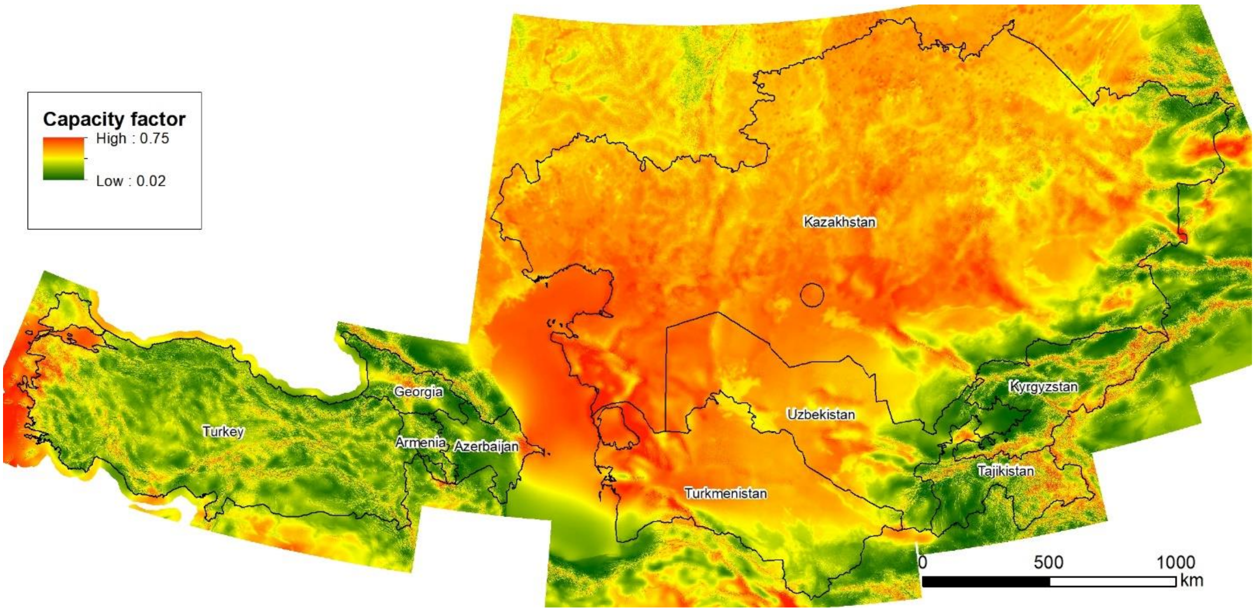
The highest values in Central Asia are found in the southern parts, in the eastern half of Uzbekistan and Turkmenistan, with values of 1500-1800 kWh/kWp. Bioclimatically and topographically it is the domain of arid or semiarid Kyzylkum and Karakum deserts, which exhibit a rather flat plateau with slight undulations. Higher values of solar irradiation and implicitly higher electricity output (1800-2000 kWh/kWp) are found in the mountains of eastern Tajikistan but the high elevation (above 3500 m a.s.l.) coupled with steep slopes and high terrain roughness make a large scale exploitation of the solar potential improbable here, except for few low power installations for local use. The western half of Turkmenistan and Uzbekistan as well as the southern half of Kazakhstan can sustain an electricity production of 1200-1500 kWh/kWp. Towards the north the values dip below 1200 kWh/kWp, under a steppe climate.

Transcaucasia is characterised by rather low electricity output from solar, i.e. 1200-1500 kWh/kWp with even lower values for the mountains in the north and southwest. The values increase to 1500 kWh/kWp and beyond that in its southern part, i.e. in Armenia and the border with Iran. The north of Turkey displays outputs of 1200-1500 kWh/kWp with even lower values for the mountains in northeast.

3.3.2 Wind potential

The wind potential is moderate displaying higher values along the mountainous ridges in southern Kazakhstan and across the open steppes eastward of the Caspian Sea (**Figure 2**). Wind has the advantage of blowing day and night, though with an irregular pattern. However, by installing wind turbines over a large area this shortcoming is diminished by reciprocal compensation of areas with and without wind. This feature is useful both for local and regional use of wind generated electricity as well as for its transmission over long distances.

Figure 2 - The wind potential in the Central Asia study area



Source: (Technical University of Denmark (DTU) in partnership with the World Bank Group, 2019)

The wind characteristics (speed, direction and regularity) are closely related to the global flow of air masses, to the development and regional evolution of air masses as well as to the underlying landforms (elevation and roughness). As a rule, flat and open areas (including water surfaces) as well as the upper part of mountain ridges experience the highest wind speed. These areas usually yield a higher capacity factor, above 40%. Such areas are located in central and eastern Kazakhstan, eastern Turkmenistan and Uzbekistan and the northern and eastern shores of the Caspian Sea. Locally, high wind speed and high capacity factors are encountered on the tall mountain ridges in eastern Kyrgyzstan and Tajikistan. Here, the high elevation combined with the steep slopes and a difficult access, make the wind potential suitable mainly for local use, given the low population density of these areas.

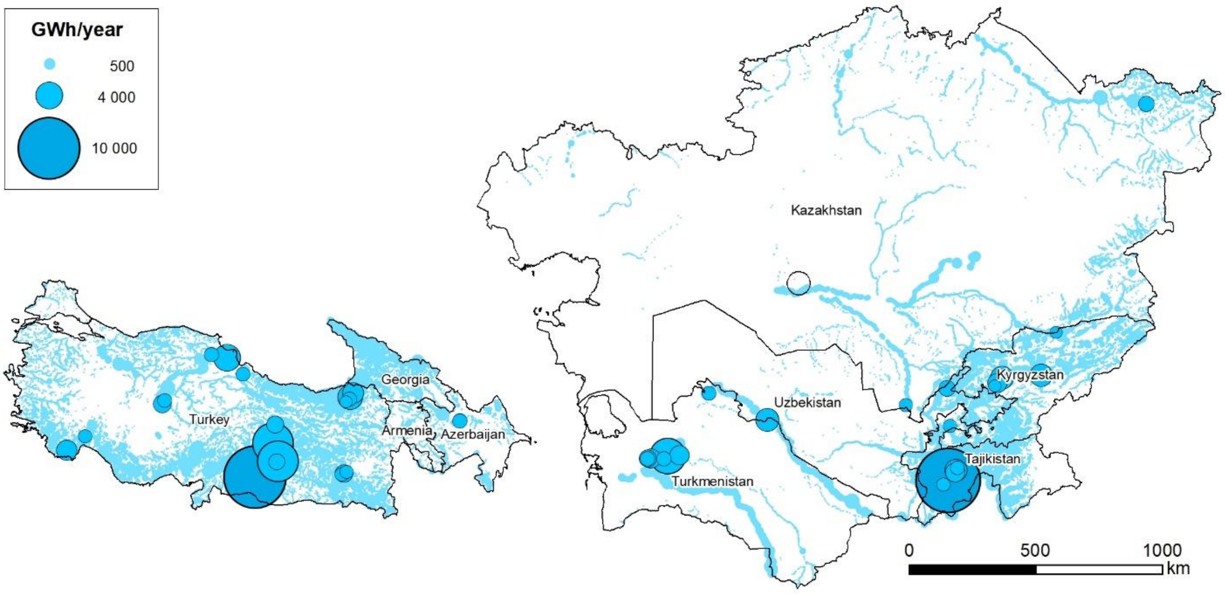
The average wind speed decreases significantly on the northern slopes of the aforementioned mountains as well as along the intra-mountainous valleys sheltered by the flanking ridges. Here, the capacity factor barely reaches 20%.

Transcaucasia displays an even more complicated and irregular wind speed behaviour due to its complex relief, with long and massive mountain chains bordering the northern and southern fringes and with their countless secondary ridges that break off from the main ones northwards or southwards. Higher capacity factor values are found in central Georgia, along the main low-lying corridors and in Azerbaijan, along the shores of the Caspian Sea. The aforementioned considerations on the tall mountain ridges in Central Asia are also valid for the Greater and Lesser Caucasus Mountains.

3.3.3 Hydropower potential

The hydropower potential of the region is unevenly distributed and varies significantly (**Figure 3**) (Hoes, Global potential hydropower locations, 2014). The flat arid and semiarid expanses, which occupy large areas in Kazakhstan, Uzbekistan and Turkmenistan, hold a minimal or even null hydropower potential. On the other hand, the mountainous areas from east and southeast Central Asia, overlapping Kyrgyzstan, Tajikistan and partly Kazakhstan hold a high hydropower potential. The same situation is found in Transcaucasia, where the northern rim - Greater Caucasus - and the southern one - Lesser Caucasus - offer a high gravitational gradient and rich water feeding from rainfall and snowfall.

Figure 3 - The hydro energy potential in the Central Asia study area



Source: (Hoes, Global potential hydropower locations, 2014)

The overall potential is only partly exploited within the region, with several rivers being intensively dammed for electricity generation: Vakhsh in Tajikistan (5110 MW), Naryn in Kyrgyzstan (2870 MW) and Chirchiq in Uzbekistan (1200 MW). The technically exploitable potential of the five countries in Central Asia is estimated at 510.1 TWh/year (Eshchanov, et al., 2019), of which less than 10% is currently used. Only Uzbekistan makes use of a significant share of its hydropower potential (40%). Kazakhstan and Kyrgyzstan exploit respectively 15% and 13% with still much room for expansion. Tajikistan, which possesses 62% (or 317 TWh/year) of the total hydropower potential of the five countries together, exploits only 5%.

The use of hydropower continues to evolve with plans for building new dams and hydropower plants (International Hydropower Association, 2019). Uzbekistan is committed to spend more than US$4 billion during next decade for building 18 new hydropower plants (although, rather of small or medium power) and modernising 14 existing ones. Tajikistan also continues the Rogun Dam project, which, when completed, will have a capacity of 3600 MW and will allow electricity to be exported. The first turbine of 600 MW started generating electricity in 2018, while the second one is expected to come online soon. Kyrgyzstan plans to overhaul its main hydropower plant at Toktogul (1200 MW), adding 240 MW to its capacity, while putting on hold, until investment is available, another planned station: Kambar-Ata-1, of 1900 MW.

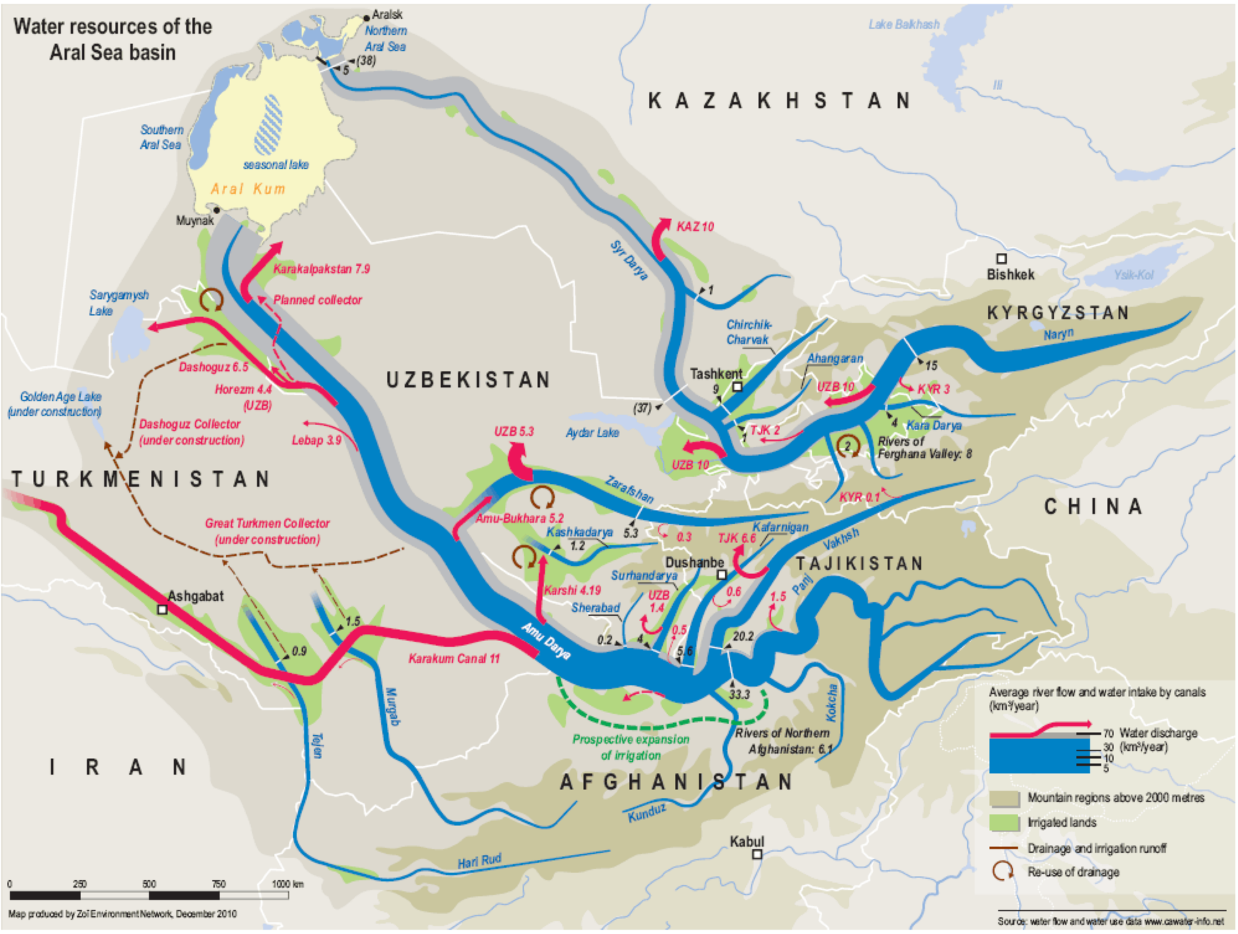
3.3.4 Water resources management and hydropower

In most cases the use of the hydropower potential goes hand in hand with (or is a part of) a wider and more complex development and management of the river basins and water resources. This is especially sensitive in places where the rivers are shared by multiple countries under (semi)arid conditions.

Central Asia has the core of its mountains in its southeaster corner acting as a water castle that feeds rivers flowing towards northern and western (semi)arid regions. Considering that the mountain area (including the main water resources) is covered by two countries while the other three lie in the lower and (semi)arid areas, the issue of water management and control becomes very sensitive. The countries downstream (Kazakhstan, Turkmenistan and Uzbekistan) rely heavily on the water for their agricultural and industrial activities as well as human consumption. Therefore, any new initiative for dam construction is met with opposition and many projects are put on hold for years (e.g. Rogun in Tajikistan).

The area had a more integrative development during Soviet times, when the water management plans were executed unitary and seamlessly without concerns over the borders (**Figure 4**) (Mercados, 2010). Dam building and canals for irrigation were joined in the same project. Following independence, the countries have pursued their own interests and goals that often clash with one another.

Figure 4 - Water resources in Central Asia

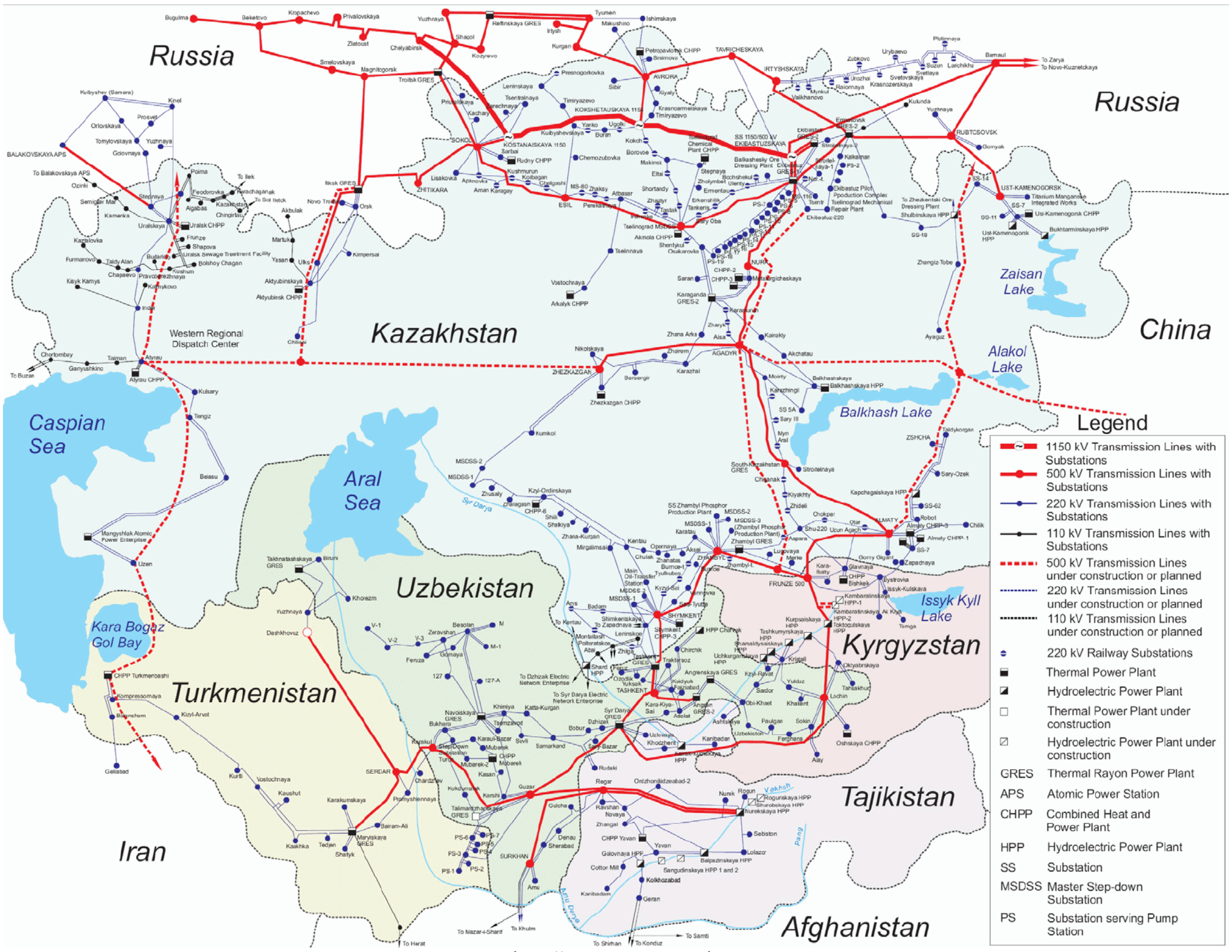


Source: www.cawater-info.net

3.4 The power transmission grid

The power grid of Central Asia (**Figure 5**) is inherited from USSR times, when the five former Soviet republics formed and ran the Central Asian Power System (CAPS) (Mercados, 2010). After independence, some of them disconnected from the system, as Turkmenistan did in 2003. This triggered actions from the other states, like Uzbekistan, which refused to transit electricity, disconnecting Tajikistan from the system. However new tendencies are apparent, such as grid reconfiguration to take advantage of better opportunities. Turkmenistan, for example, after disconnecting from CAPS, runs its grid synchronously with Iran, from which it receives frequency control services.

Figure 5 - The power grid in Central Asia



Source: http://eurasian-research.org

Most of the Central Asian grid was built throughout the 1950s, 1960s and 1970s. Since then there was not much investment into its upgrading and refurbishing. The aging power grid severely affects the quality of power supply. Uzbekistan and Tajikistan face the largest number of outages in the region, with almost six occurring every month. On average, these blackouts last almost two hours in Uzbekistan and almost four hours in Tajikistan. Other Central Asian countries experience outages at least once a month (Kyrgyzstan) or once every two months (Kazakhstan). In Kyrgyzstan they last on average two hours, in Kazakhstan this is one hour. All countries report 15% to 20% of electricity losses (World Bank, 2013) (World Bank Energy and Extractives Global Practice, 2017) (Organisation for Economic Co-operation and Development, 2019).

The region's geography with high mountains in the southwest, large deserts in the south and semiarid steppe in the west determined the location of the human settlements and consequently the power grid configuration. The power grid mimics the population distribution and has the shape of an unclosed circle around the deserts and steppes found in the middle of the region, centred on the Aral Sea. The northern and eastern rims of the circle are the most developed and continuous, with many parallel branches and extensions into adjacent areas. The southern one, in Turkmenistan and Uzbekistan, becomes thinner and one-threaded while the eastern one lacks continuity, having a gap between the Kazakh and Turkmen grids.

The backbone of the system is the 500 kV main line coming from the Russian Federation in the north and pursuing through all the former Soviet republics of Central Asia, ending in Turkmenistan. A 220 kV lattice doubles it and extends it into adjacent areas.

The network forms loops in areas with higher population density, as in northern and southern Kazakhstan, south-eastern Uzbekistan and partially Tajikistan. It has many dead-end branches in the large arid expanses in the south and west (Turkmenistan and western Kazakhstan) as well as in the valleys of mountainous Tajikistan and Kyrgyzstan. The central area of Kazakhstan, around the Aral Sea, has the lowest grid density.

The grid is patchy in remote areas. Due to the special configuration of the country's borders and its relief, parts of the country's power grid are not connected. In this case, connections are made via neighbouring countries. This is a legacy of the initial design, during USSR times, when the internal borders had less relevance. Numerous examples can be found in the region: the western part of the Kazakh grid is not directly connected with the rest (and most extensive part) of the country, but through the Russian Federation in the north. Parts of Kyrgyz, Tajik and Turkmen grids are connected via Uzbekistan. Turkmenistan, located at the end of the main line and its branches, is the least integrated into the common grid. Uzbekistan, on the other hand, is the pivot of the area, closely connected with the other four.

The large empty spaces that characterise the realm make transmission lines costly to build and to maintain. There are, however, plans of linking the western grid of Kazakhstan with the main one in the east and to reinforce the network by building additional lines in areas with high voltage transmission lines.

Given the initial design of the power grid, the five Central Asian countries are well interconnected, although parts of one country might be completely fed by the neighbour.

Since CAPS was designed as a southern extension of the Russian electricity system, the connection with the northern neighbour is still extensive, with a network of lines intricately linking the settlements of northern Kazakhstan with the ones in southern Russia.

At the southern and eastern fringes, the connections with neighbours are patchy and only serve local trade. No connection currently goes to China, although there are plans for a Chinese major export power link into the region and even further, to Europe. There are also plans for a southern reinforcement of the grids and interconnections with Afghanistan and further to Pakistan.

4 Cost map and optimal path

4.1 Concept

The main aim is finding the optimal route between two points, considered as starting and ending point. In a homogenous, isotropic space, this route would be the straight line that connects both points. Real space is however different, with properties (e.g. relief, elevation, land use) varying from place to place, which incur different costs or efforts to cross it. On top of physical space characteristics, a social and economic dimension can be included, which can increase or decrease the crossing effort. Thus, to every point in a considered space a crossing cost can be allocated, which acts as a brake or as a friction surface. These points take the form of cells or pixels in the modelled format. The mass of these points accumulates to form a friction map that is used as a basis for computing the optimal route, which in this case would follow the "cheapest" pathway between the considered points.

The minimum value of the crossing cost is zero, in which case the respective pixel is considered as ideal to crossing, virtually without obstacles. There is practically no maximum value, but a very high value would be sufficient to act as a barrier, excluding the concerned pixels as candidates for the optimal path's passage.

Depending on the perceived "difficulties" of the considered (user-defined, case-study specific)) variables, the cost value attributed to a pixel can reach values sufficiently large, so that the algorithm for computing the optimal route considers them as barriers to crossing. In such case, the concerned pixels are avoided, the choice being made for a "cheaper" path.

The final cost map represents a composite weighted map of the constituent variables. The variables, which constitute this composite map, their weights and score classes are presented in the chapter Scenarios and Discussions.

The score attached to a pixel is not attributed within an absolute framework. As such, a value of ten does not mean that the pixel is ten times less valuable than that a pixel with a value of zero, as these values are relatively related to the perceived easiness to cross the space. For example, if an area is flat (slope under 1.15 degrees) it is considered as not causing any special problem for building and consequently a zero value is assigned, which practically represents a "lubricated" surface onto which the crossing proceeds with ease. On the other hand, a plot with a slope in the range of 4.50-8.50 degrees can pose noteworthy building problems that require special solutions and higher costs. In this case a cost or friction score of four could be allocated. This does not necessary mean that the costs for crossing would be four times higher, but it is the result of a user-made decision that the respective plot is four times harder to be crossed than the flat plot. Zones with steep slopes (above 16.50 degrees) will be scored with high values (e.g. nine), which renders them practically avoidable, no-go zones. In such a way, zones can be made favourable or unfavourable to crossing.

Once the cost map is available, the optimal path can be computed between the pre-defined starting and ending point. It starts from the starting point and proceeds by cumulating the least cost of the neighbouring cells towards the ending point.

The methodology underlying the approach references the work of (OECD, European Union, Joint Research Centre - European Commission, 2008) and (Becker, Saisana, Paruolo, & Vandecasteele, 2017) on constructing composite indicators. The work of (Eastman, 1999) (Voropai & Ivanova, 2000) (Malczewski, 2006) (Boroushaki & Malczewski, 2010) and (Greene, Devillers, Luther, & Eddy, 2011) on multi-criteria decision analysis are used as basis for the underlying theory of choosing the components of the analysis.

The principles of choosing of the layers, their grouping, scoring and weighting follow the approach of (Bagli, Geneletti, & Orsi, 2011) and (Eroglu & Aydin, 2013).

Finding the least-cost path is a common operation that most GIS software can perform by integrating modules for the computation. However, the choice or building of the cost surface, on which this computation is based, remains the user's responsibility.

Similar work for the routing of power lines has been previously performed by (Monteiro, et al., 2005), (Bagli, Geneletti, & Orsi, 2011), (Dedemen, 2013) and (Eroglu & Aydin, 2013).

The focus of the analysis carried out by (Bagli, Geneletti, & Orsi, 2011) was on minimising the impact of the power line on human health, landscape and ecosystems. Within the three aspects addressed, it took into consideration the characteristics of buildings (density, distance and average height) as proxy for human health, distance and visibility from cultural and recreational sites as proxy for landscape and terrain parameters (aspect, elevation), distance from infrastructure corridors and degree of naturalness for the ecosystems. Their approach was customised to the local conditions and assets, implying a high-density of population, settlements and infrastructure and a particular caution to the cultural landscape and wildlife. As the main concern was the human health, this group received more weight in their analysis.

(Eroglu & Aydin, 2013) put more emphasis on the terrain characteristics like slope, land cover, geology, landslides, hydrography and already existing linear infrastructure (roads).

(Dedemen, 2013) mainly uses layers carrying terrain characteristics, such as elevation and slope, soil and geology, water resources and protection areas, land use and settlements, and also existing infrastructure, like roads, pipelines and other transmission lines.

The approach presented here also considers the above aspects but, as the analysis covers a much wider area under a much coarser spatial resolution, some minute features are excluded while more relevant ones are included. Moreover, the concerned area is sparsely populated and includes large empty spaces (deserts, steppe etc.).

4.2 Assumptions

Every approach for finding least-cost paths requires building a cost surface. The cost surface may consist of a single original layer or a composition of multiple layers. Further, it may hold the original values (e.g. actual elevation or land value) or may be re-classified to a score based on an algorithm.

The number of variables taken into account varies according to the scope, level of detail, knowledge and data availability. Usually, prior models validated through practice form the basis of the approach. Novel approaches require, however, a prior theoretical exercise, considering a set of assumptions regarding the factors influencing the result of the model.

As the scope of this study is to find the least-cost path or optimal route for a power transmission line from eastern Central Asia to Europe, the assumptions are related to the number of variables taken into account, their importance or weight in the analysis and their values.

An infrastructure building work implies evaluating the terrain crossed under all its natural and anthropic aspects, each with its own characteristics and importance. As the decision of the crossing suitability must be based on a value that is the resultant of all variables involved, a method for aggregating theses variables must be devised. This is usually done by developing composite indicators, which are mathematical combinations (or aggregations) of a set of indicators. The same principles are used for aggregating and combining the individual layers into a composite cost surface with a final cost value for every pixel. The Joint Research Centre has solid experience in developing frameworks to construct composite indicators (OECD, European Union, Joint Research Centre - European Commission, 2008) (Becker, Saisana, Paruolo, & Vandecasteele, 2017).

The **first assumption** refers to the nature of factors involved in influencing the route of a power transmission line. Following previous work undertaken on this topic, geographical and environmental factors of the terrain (elevation, slope, soil, geology, water bodies, and natural hazards) are assumed to be crucial, as their characteristics determine the limits of the building possibilities as well as the economic opportunities.

Since the underlying scope of the envisaged power interconnection is the transfer of clean (and cheap) electricity, the local RES potential represents an important factor in routing the power link, maximising its collection efficiency. Finally, several socio-economic factors have a strong influence on the costs and the building possibility (at least temporary) of electricity transmission infrastructure. These are related to the land use (and its entailed land value), political and military conflicts (as repelling factors) and the proximity to already existing infrastructure (as attracting factor).

Although the economic and investment mechanisms are essential for building a power interconnection, this study does not consider these factors.

Obviously, more factors can be included for a more detailed analysis, e.g. calculations where the routing must obey specific constraints, like avoiding densely populated areas or zones with high cultural value.

The **second assumption** concerns the scoring used for the cost map. There are two aspects to be considered here:

- the number of classes issued within the same dataset and their associated score;
- the break-up values used to create the classes.

The number of classes created depends on the nature and property measured by the variable. The scoring for most of the layers uses a 10-class range, from zero to nine, with zero being the most favourable to crossing (no friction) and nine the most adverse. It is assumed that 10 classes cover most of the situations encountered on the field. In addition, the degree of increment used makes it possible to label any situation met. In some cases (earthquakes, landslides and floods), the number of classes and the breakup values applied to split them are used as in the original dataset, with the same number of classes and the same score. In other cases (slope, land use and distance to existing substations), they are inferred from previous works (Monteiro, et al., 2005), (Bagli, Geneletti, & Orsi, 2011), (Dedemen, 2013) and (Eroglu & Aydin, 2013) amended with own assumptions.

Some classifications are based on own assumptions (elevation, soil erosion, conflicts and protected areas). Here, the most favourable and most adverse conditions are identified and scored accordingly: zero for the former and nine for the latter. Although, the highest score (nine) does not exclude the area from being crossed, it imposes a tenfold resistance to it. It still can be overrun, however, only when no other better option exists.

It is to be noticed that there is always a most favourable class, with score zero. However, there is not always a most unfavourable one, with score nine. In this case, besides the most favourable areas, other areas have been defined, which are less favourable by a certain degree. They are given an intermediate score. This is the case for the soil erosion, protected areas and distance to substations datasets.

For scoring the RES potential, a different assumption is made. The potential is assumed to be always favourable irrespective of the value. Therefore, it is ranged between zero and one, with the highest potential value corresponding to zero (lowest friction) and the lowest potential to one.

The **third assumption** involves finding the right combination of layers and their weighting. This is done based on the presumption that similar factors have similar effects. Therefore, they are grouped by their type and similarity, forming five groups. From here derives the subsequent assumption that the influence of these factors and groups of factors is not the same. Some factors and groups have a higher influence and therefore are given a higher weight in the final calculation. This is the case for the nature of the terrain and the land use/cover, which determine the physical background, against which the infrastructure is built. Further, they control the population's distribution and to some extent the economic activities' location.

The RES potential is presumed to have a high weight since it influences the effectiveness of the RES-generated electricity. The group of natural and human-induced hazards receive a lower weight mainly due to the coarse spatial resolution at which these datasets are obtained. For a small-scale analysis with a high level of detail of these factors, their weight could be increased.

The actual values of the weights are not a matter of precise measurement or mathematics but are based assumptions. Their appropriateness may change with the altering of the scale and constraints of the landscape, which is possible in the model produced.

A base or reference scenario based on the aforementioned assumptions and two alternative scenarios are presented in following chapters. The GIS model allows customizing the approach by including the desired number of variables, their grouping and weighting, as well as re-classifying the original values.

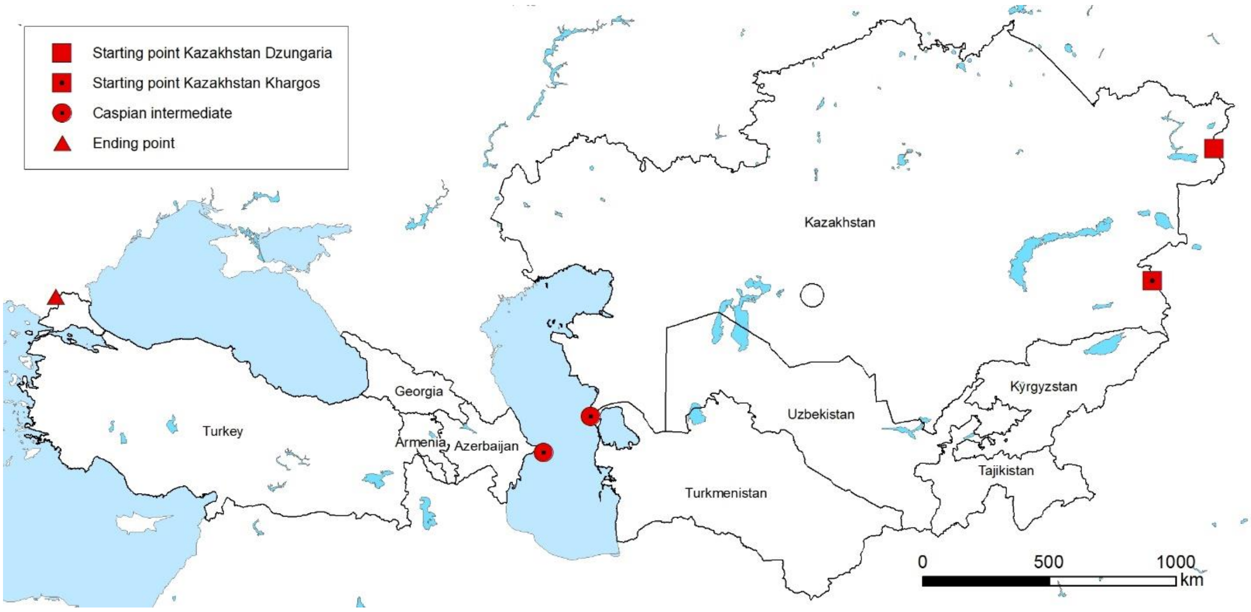
4.3 End points selection

Optimal path computation requires at least two points to be defined. In this study two extremity points (called starting and ending point) and several intermediate points are fixed (**Figure 6**), as explained further.

The departure point of the route is fixed at the easternmost extremity of Kazakhstan, in order to collect the full potential of RES along the entire crossing of this country in westward direction. In a second version of the base scenario, another starting point is defined, still located in the east, at the border with China, at a possible future development site of the dry port of Khargos.

Given the geopolitical circumstances, a spatial prerequisite, is avoiding Russia and Iran. In this situation the Caspian Sea must be crossed to Europe, requiring the use of submarine power cables. Crossing the Caspian Sea is the easiest (technically and economically) at its narrowest sector, while avoiding the deepest zones. In this regard, for the base scenario, on both shores two anchor points are defined for the endings of the submarine part of the power cables. The point located on the eastern shore of the Caspian Sea represents the terminus for the route that crosses the Central Asian countries. The point located on the western shore represents the starting point for the second segment, which crosses Transcaucasia and Turkey until its westernmost point, where the ending point is located.

Figure 6 - The end and intermediate points



For the other scenarios, no anchor points are defined on the Caspian Sea's shores. Instead, the algorithm is allowed to find the best suitable path across the sea because of the constraints imposed over the land.

The westernmost terminus of the route is placed on the three countries' border of Bulgaria, Greece and Turkey, at the EU's border.

4.4 Composition of the cost map

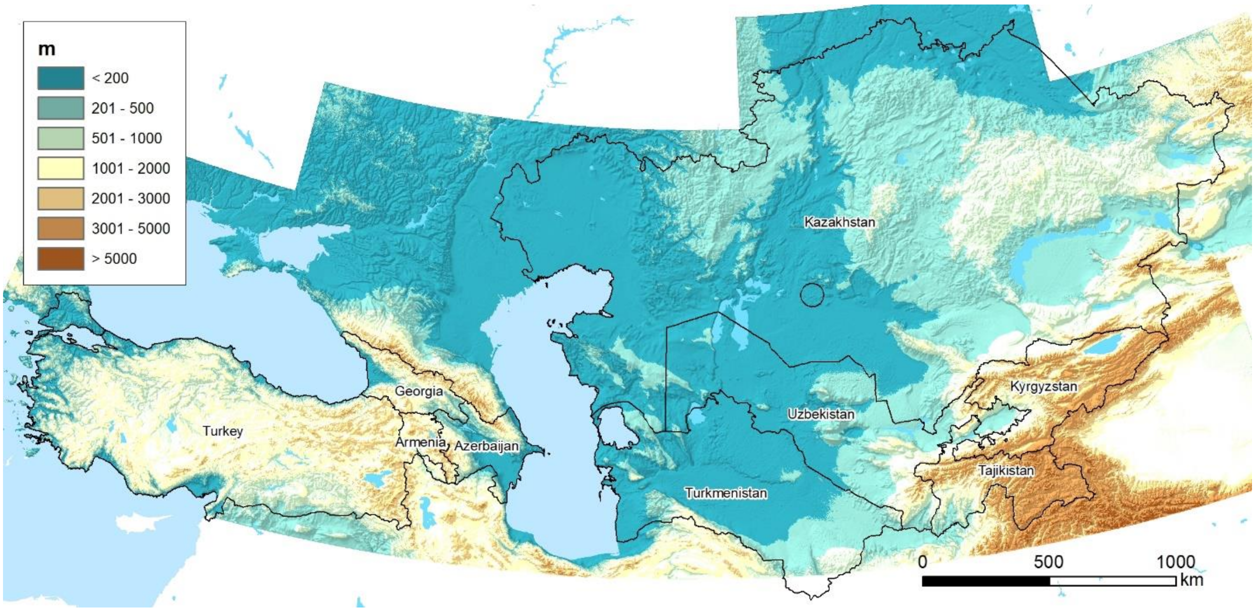
4.4.1 Terrain parameters

Elevation

Elevation influences the economic activities mainly through the effects of climate characteristics (temperature and air pressure). The air becomes thinner as the altitude increases, interfering with the human effort capacity. Elevation induces modification of climate parameters with impact on the weathering processes and the nature and intensity of the terrestrial modelling agents. Thus, depending on latitude and local climate and relief conditions, a rise in elevation triggers morphogenetic processes such as gelifraction (frost and thaw alternation), soil frost on longer periods of time and to greater depths (presence of permafrost – permanently frozen ground), glacier presence and usually an increase in steepness and roughness. These processes lead to an intensive rock crumbling through frost-thaw repetition of the water caught in the rock fissures, which forms an issue for building and infrastructure works. The occurrence of permafrost requires finding special solutions for building to prevent the sinking of foundations and ultimately the destruction of the buildings or infrastructure works. All these processes involve an intensive morphological dynamic and rise special problems to building and maintenance activities, which ultimately translates in higher costs.

The elevation data used (**Figure 7**) is collected in 2000 during the Shuttle Radar Topography Mission (SRTM) (Jet Propulsion Laboratory, 2000), processed to correct errors and fill voids (i.e. no data). The data, with the shape and size of 3° (latitude and longitude) tiles, have been downloaded and assembled to the area of interest. Its spatial resolution of 90 m (i.e. a single elevation value for a square-shaped tile of 90X90 m) is sufficient for detailed analysis over large areas. This dataset, having the finest resolution, is used as a model to adjust the spatial resolution of all the other datasets.

Figure 7 - The elevation map of Central Asia



Source: (Jet Propulsion Laboratory, 2000)

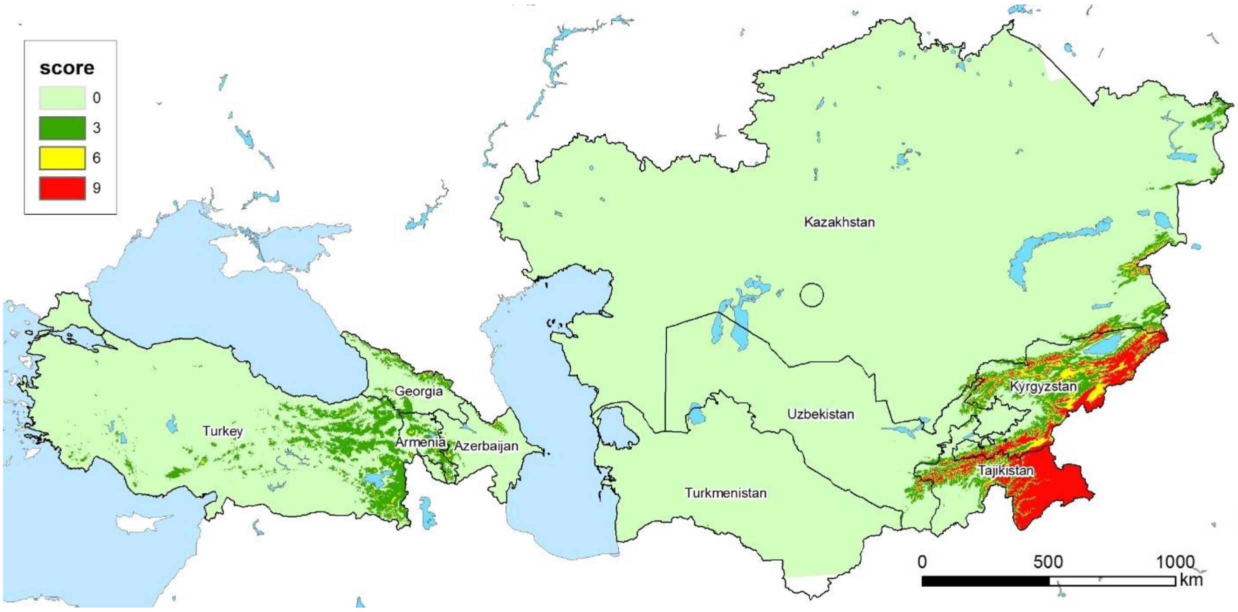
Based on this dataset, the slope was calculated as a derived parameter, with a role in building the friction map.

Four classes of elevation have been defined for the friction map (**Table 3** and **Figure 8**).

Table 3 - The classification of the elevation dataset

Elevation range	Issue description	Friction score
≤ 2000 m	Without particular problems for the work and effort capacity; any type of infrastructure can be built.	0
2001-3000 m	Thinner air; at 2000 m altitude, the air pressure is ⅔ of the sea level value; it can pose problems to people with circulatory deficiencies; building works can proceed with difficulty.	3
3001-3500 m	Transitional elevation range where, in the lack of alternatives, infrastructure can be built.	6
> 3500 m	Elevation level which may inflict significant problems to most people; building works and subsequent maintenance proceed with difficulty and are costly; to be avoided if possible. Gelifraction processes and permafrost start to occur at the considered latitude.	9

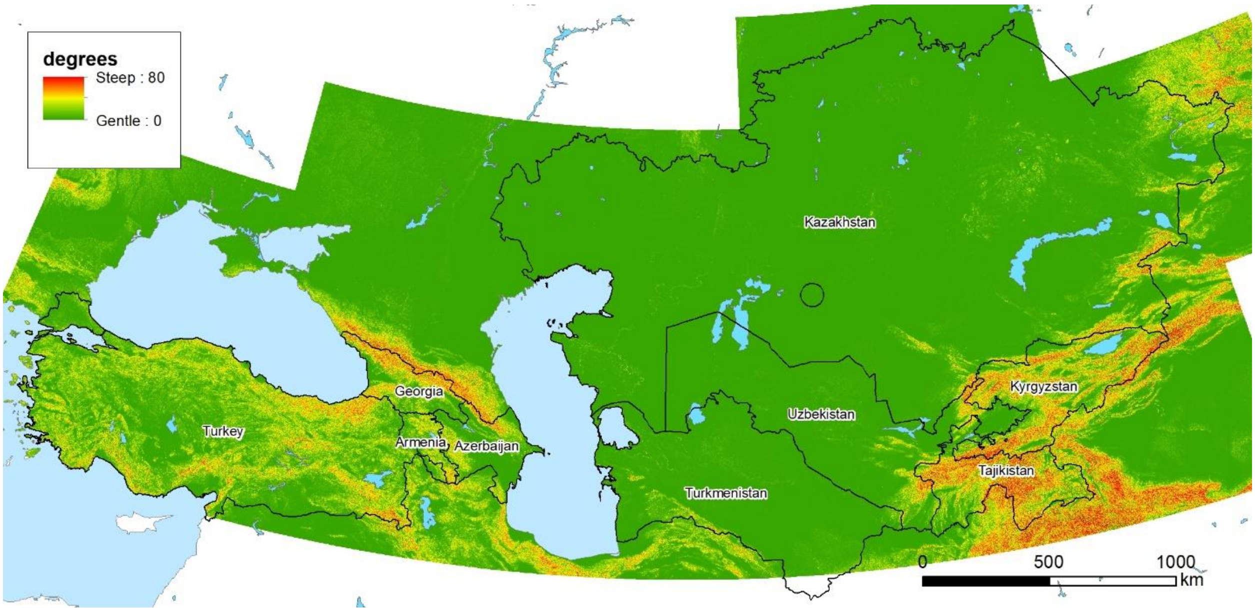
Figure 8 - The classified elevation in Central Asia



Slope

The ground stability under a specific slope (**Figure 9**) is closely related to the nature of the substrate. The angle of repose varies even for the same material, especially for the soft ones (sand, clay, marl, shale), depending on the presence of water and the degree of loading with vegetation or buildings. A series of slope processes (soil erosion, landslides, creep, rock falls and collapse, avalanches) are triggered at certain values of steepness and the economic activities (building works, maintenance and ease of access) are influenced by the slope value.

Figure 9 - The slope map of Central Asia



Most classifications (**Table 4**) consider terrains with slope values of 0-2% / 0-1.15° as horizontal or almost horizontal, without the display of slope processes. Terrains with slope values of 2-8% / 1.15-4.50° are considered as being gently sloping, with the rise of some slope processes: slow downward movements of soil and superficial deposits (creep), sheet erosion and gully formation. Terrains with slope values of 8-15% / 4.50-8.50° are categorised as having a small declivity, with the aforementioned processes growing in intensity. At these values, also depending on the geological settings, landslides can be triggered. Terrains with slopes of 15-30% / 8.50-16.50° are considered as having moderate steepness, where the slope processes (sheet and linear erosion, landslides, rock falls and other) start to be significantly visible. Following stabilisation works at reasonable costs, the aforementioned terrain categories can be considered as suitable for various economic uses.

Table 4 - Slope classification by various authors

Source	Break values for slope classes
(Kassam, van Velthuizen, Fischer, & Shah, 1993)	0-2-5-8-16-30-56%
(Edmonds, Thomas, Simpson, & Baker, 1998)	0-2-7-15-25->25%
Soil Information Service Canada (Canada, 2013)	0-3-9-15-30-60->60%
(van Zuidam, 1979)	0-2-4-8-16-35-55->55°

Slope values are derived from the elevation dataset using functions of ArcGIS 10.1 software.

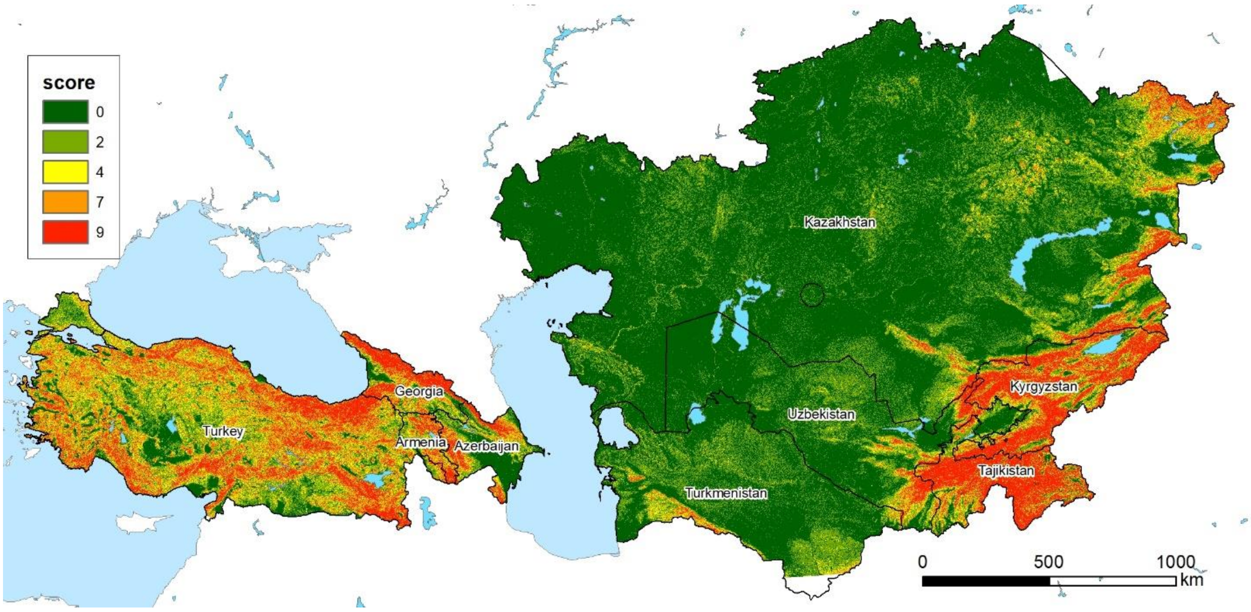
Wind turbines usually require horizontal or gentle slopes for their building site but they can be placed in almost any geomorphological context and landscape where the wind frequency and speed are high enough. Solar panels have the highest efficiency on horizontal and low declivity terrains, up to 30% / 16.50°. Beyond these values, the limitations induced by the slope orientation (aspect) can result into a significant decrease of efficiency. On terrains with slope above these values, the required works for diminishing the effects of slope processes as well as the subsequent maintenance can significantly increase the involved costs. Access roads built on such terrains require higher building and maintenance costs.

The slope categories have been scored in order to reflect the crossing easiness (**Table 5** and **Figure 10**).

Table 5 - The classification of the slope dataset

Slope category		Friction score
%	°	
0-2	0-1.15	0
2-8	1.15-4.5	2
8-15	4.5-8.5	4
15-30	8.5-16.5	7
>30	>16.5	9

Figure 10 - The classified slope in Central Asia



4.4.2 Land use and protected areas

Land use/cover

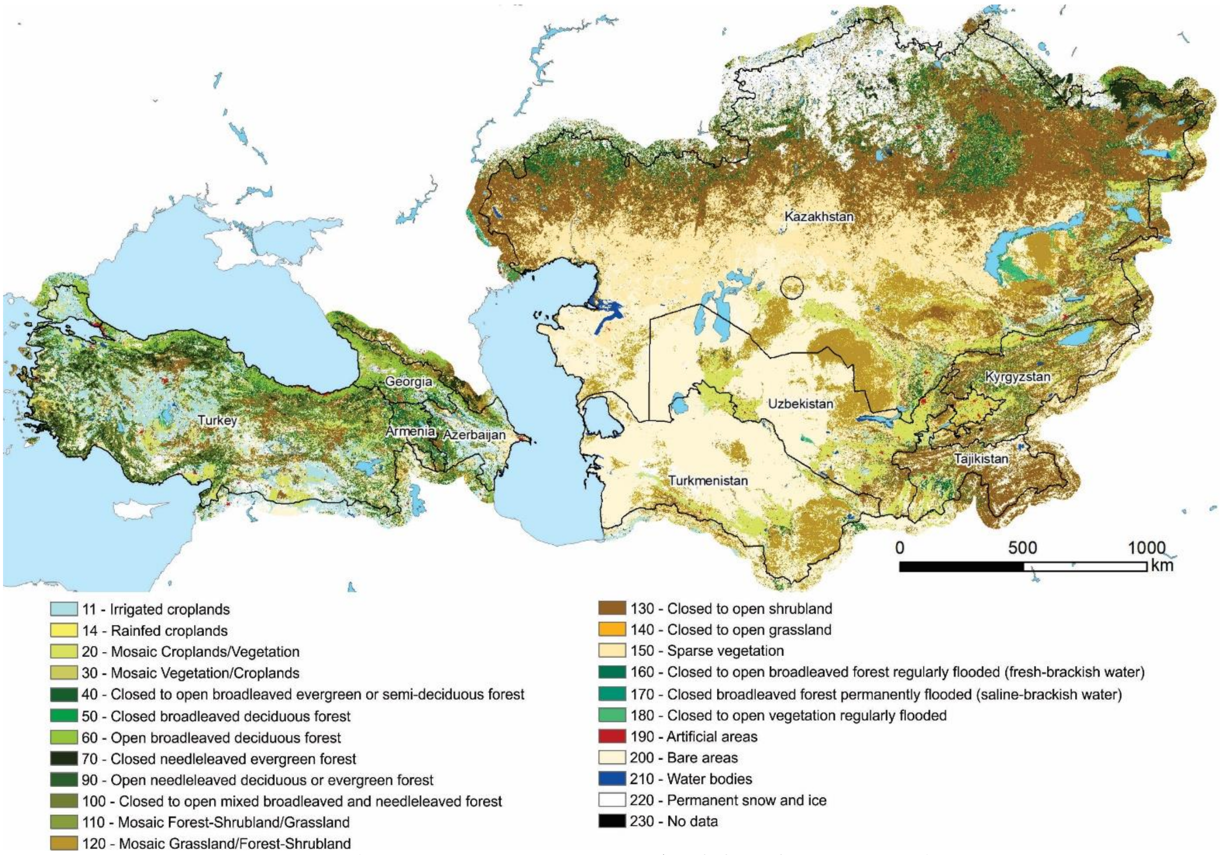
Land use/cover displays the type of activity operated on a certain plot. From this dataset the suitability for specific uses can be inferred. As not every piece of land is included into an economic activity, this dataset can also contain land cover categories, which represent the natural state of a terrain.

Land use/cover represents a crucial parameter in any territorial planning activity. Depending on the aim, some categories are preferred while others can impose limitations. Power transmission infrastructure usually does not require a large area. The footprint of transmission lines is not larger than the one of a road with the advantage that the terrain surface is unoccupied (except the pillars' base) and as such it can be used for other activities (agriculture, pasture or it can be left in its natural state). However, in areas with a high level of economic activity, human habitation or with vertical development of features on the ground, the transmission power lines can have a disruptive impact. They require unhindered access for maintenance and power failure remedial, as well as a protection buffer (called Right-Of-Way, ROW) for safety operation, which extends laterally from the line axis with a distance proportional to the voltage rate (up to 100-120 m). Such wide corridors are hard to find in densely populated areas or industrial zones. It is difficult to change the destination use of such lands or it is very costly to cross them using methods and technologies with a lesser visual and functional disruptive impact (e.g. underground power cables).

The same considerations are valid for areas with intensive agriculture, irrigations, orchards and forests. The cost of crossing these lands would be higher due to the necessity of clearing the ROW (i.e. cutting the forest).

The data for the land use/cover (**Figure 11**) are obtained from the Globcover web-platform (European Space Agency; Université Catholique de Louvain, 2010), an initiative of the European Space Agency initiated in 2005 in collaboration with other institutions, with the aim of developing a service able to provide spatial datasets on land use/cover with global coverage. The input data come from the MERIS sensor on board of the ENVISAT satellites, with a spatial resolution of 300 m. For this analysis, the GlobCover 2009 version was used. This version is the latest produced offering a seamless coverage over the study area. Comparisons with similar newer but patchier products show that the land use/cover categories do not undergo major changes during this time period.

Figure 11 - The land use/cover in Central Asia



Source: (European Space Agency; Université Catholique de Louvain, 2010)

The dataset contains 28 land use/cover classes present in the studied area, which were reclassified for the cost map (**Table 6** and **Figure 12**).

Table 6 - Land use/cover classes and reclassification scores

GlobCover code	Description	Friction score
10	Mosaic cropland rainfed	1
11	Post-flooding or irrigated croplands (or aquatic)	1
12	Post-flooding or irrigated shrub or tree crops	1
20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	2
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	1
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	1
50	Closed (>40%) broadleaved deciduous forest (>5m)	3
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	3
70	Closed (>40%) needleleaved evergreen forest (>5m)	3
80	Closed (>40%) needleleaved deciduous forest (>5m)	3
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	3

GlobCover code	Description	Friction score
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	3
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)	3
120	Mosaic grassland (50-70%) / forest or shrubland (20-50%)	1
130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	1
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	1
150	Sparse (<15%) vegetation	2
153	Sparse (<15%) trees	1
160	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water	3
170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water	3
180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	1
190	Artificial surfaces and associated areas (Urban areas >50%)	9
200	Bare areas	1
201	Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)	1
202	Non-consolidated bare areas (sandy desert)	1
210	Water bodies	9
220	Permanent snow and ice	9
230	No data	1

Figure 12 - The reclassified land use/cover in Central Asia

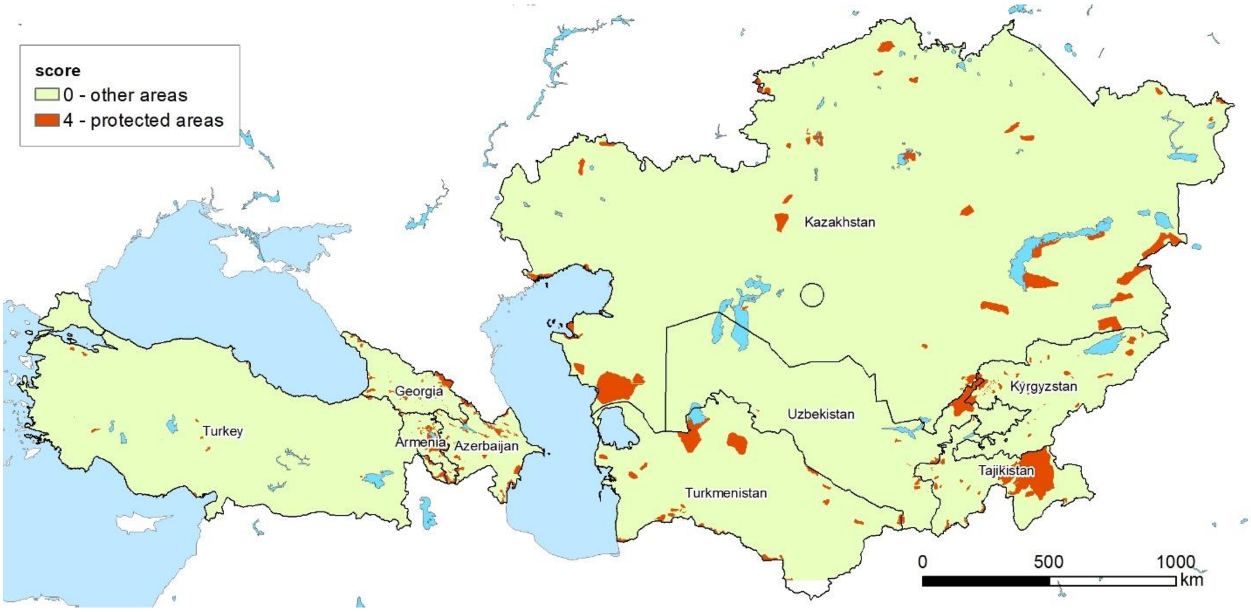
In general, the areas covered by crops, grassland, shrubland and bare areas are the most favourable lands for power infrastructure building, therefore they received the most favourable score in the reclassification scheme. In addition, the lands on which the forests cover relatively small areas in association with the already aforementioned categories, have received the same score. The lands covered predominantly by forests are scored three. The least favourable score (nine) is assigned to residential/urban areas (high building costs, many and hard to obtain permits, regulations and limitations), water bodies and those permanently covered by ice.

Protected areas

Another spatial dataset with an important role in the territorial planning activity is represented by the protected areas. Depending on their protection regime, the type and intensity of economic activities allowed inside these areas may vary. The biggest impact, especially against the avifauna, is produced by the power transmission lines and by the wind turbines that pose a threat to birds through their turning blades. These areas are to be avoided as much as possible for building works or, when they are unavoidable, their impact must be kept at a minimum, particularly by choosing the shortest pathway.

The data regarding the protected areas come from the relevant geographic dataset from the World Database on Protected Areas (WDPA) retrieved from the web platform www.protectedplanet.com (UNEP-WCMC & IUCN, 2019). This is managed by the United Nations Environment World Conservation Monitoring Centre (UNEP-WCMC) with the support of the International Union for Conservation of Nature (IUCN) and its division – the World Commission on Protected Areas (WCPA). The dataset was downloaded in vector format and was subsequently converted into raster format to be compatible with the nature of the analysis. Protected areas received a friction score of four for building the cost map (**Figure 13**).

Figure 13 - The protected areas and their classification in Central Asia



4.4.3 Renewable energy sources potential

Solar

The solar potential has the advantage of being predictable at the season level. The solar potential of the Central Asian and Transcaucasian countries, although not impressive, is larger than that of most European countries, being comparable with the potential in southern Europe. Given the large latitudinal and longitudinal extension of the Central Asian region, the electricity generated through solar energy could be transmitted in a north-south or east-west direction when local demand does not cover production. The large flat steppe expanses (prairieland, grassland) are favourable for photovoltaic (PV) installations, without significant site improvement costs.

The solar potential data used originates from the web portal Global Solar Atlas, a combined work of Solargis and ESMAP (Solargis s.r.o. on behalf of the World Bank Group, 2019). For the Central Asian region, the aggregated data (annual averages) are calculated over a period that spans from 1999 until 2015. The data that form the basis for the calculation comes from three data providers: EUMETSAT, the Japanese Meteorological Agency and the National Oceanic and Atmospheric Administration – NOAA, which manage five geostationary satellites located on key spots. The data is later corrected with information received from the terrestrial stations. Elevation data is used to generate the horizon profile with plays a role in calculating the effect of terrain shading. The simulation of the radiant energy quantity is done at a temporal resolution of 15 minutes. The spatial resolution is 1 km.

For the analysis, the PV electricity output obtained directly from the portal is used. It includes, besides the direct and diffuse solar radiation, the temperature correction, the azimuth and the optimal angle, as well as the topographical obstacles. The PV electricity output:

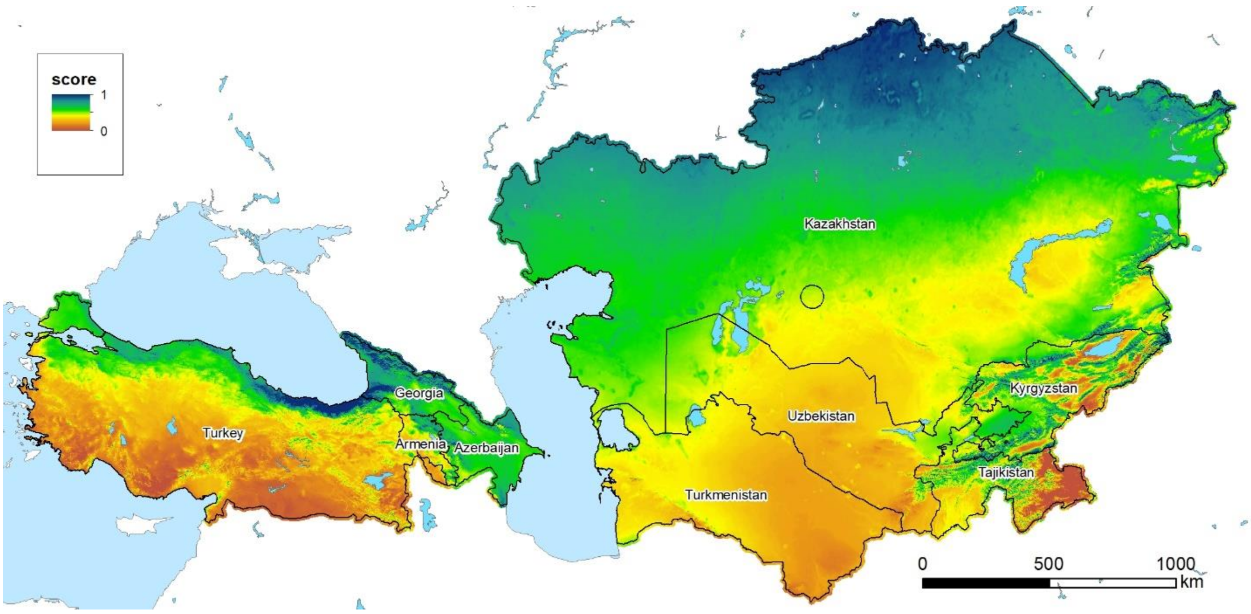
- takes into consideration a hypothetic generic type of panel as an average of the most common panels found in operation;
- does not consider the performance degradation suffered in time by the panel;
- is corrected with the temperature.

The unit of measurement is kWh/kWp, which expresses the quantity of electricity produced annually by each installed kW.

The medium values of the solar irradiation make PV panels the most appropriate technology for the region, in comparison with the concentrating solar power (CSP) technology.

In order to be used in the analysis as comparative element with the other renewable potentials (wind and hydro), the dataset has been normalized, with the values expressed as a range between zero and one (zero for the lowest and one for the highest value). For the cost map, these values are inverted, the highest potential having the lowest friction score, i.e. zero (**Figure 14**).

Figure 14 - The solar potential classification in Central Asia



Wind

Although it does not show vast wind potential, the large size of the region and its easy accessibility – flat steppe expanses without major morphological accidents – make wind-generated electricity worthwhile to be considered. The disadvantage of the wind irregularity can be compensated by placing the wind turbines over a wide area, which diminishes the local climate effect.

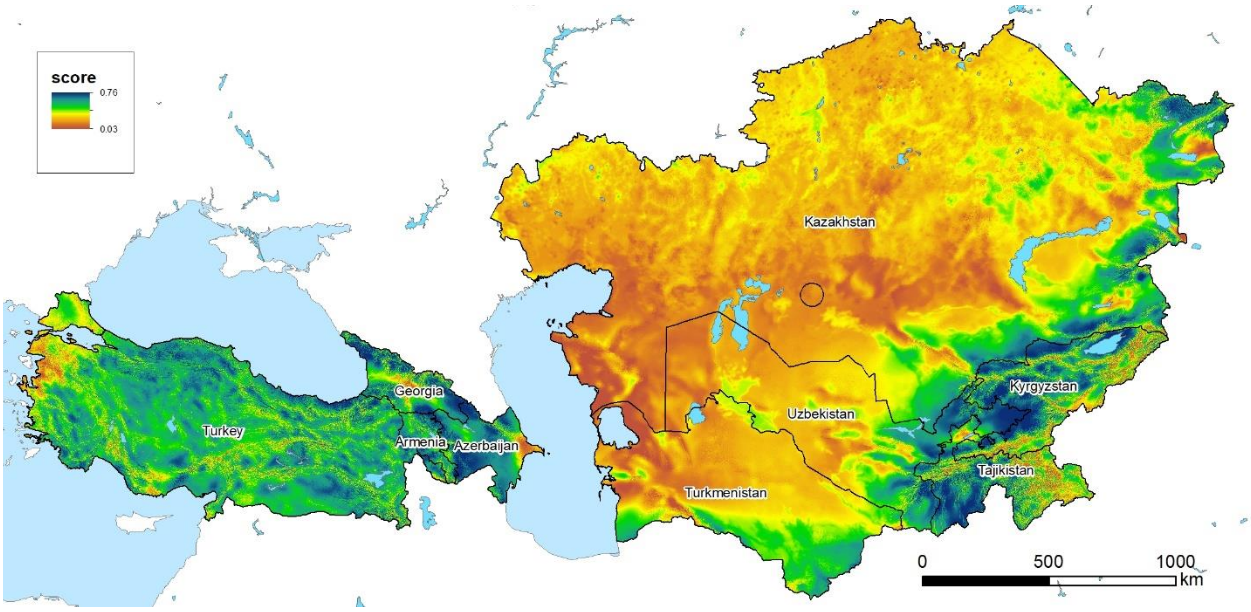
The wind potential data comes from the portal Global Wind Atlas (Technical University of Denmark (DTU) in partnership with the World Bank Group, 2019), a common initiative of the Technical University of Denmark and World Bank, financed through the Energy Sector Management Assistance Program (ESMAP). The database used in the analysis is ERA Interim from the European Centre for Medium-Weather Forecast (ECMWF). These data cover the time span from 1979 until present and are provided by a series of polar orbital satellites belonging to NOAA (VTPR, TOVS, ATOVS) and the Defense Meteorological Satellite Program DMSP (SSM/I, ERS /SCATTEROMETER) as well as by three geostationary satellites (DMSP, GOES and Meteosat).

The measurement of the wind characteristics (speed and IEC capacity factor for three turbine classes – I, II and III) is performed at three relative altitude levels: 50, 100 and 200 m. In modelling the wind speed and direction at microscale, elevation data (Shuttle Radar Topography Mission - SRTM) is used, resampled at a 150 m resolution. Terrain roughness is also taken into account in the modelling with land use/cover data coming from GlobCover 2009 Land Cover Map (European Space Agency; Université Catholique de Louvain, 2010) at a 300 m spatial resolution. The vertical profile of the wind speeds is corrected with altitude and topography. Data comes with a spatial resolution of 1 km.

For the analysis the capacity factor determined at 100 m height is used by averaging the capacity factors of the three turbine classes.

The dataset has been normalised, with the values expressed as a range between zero and one (zero for the lowest and one for the highest value). For the cost map, these values are inverted, the highest potential having the lowest friction score, i.e. zero (**Figure 15**).

Figure 15 - The wind potential classification in Central Asia



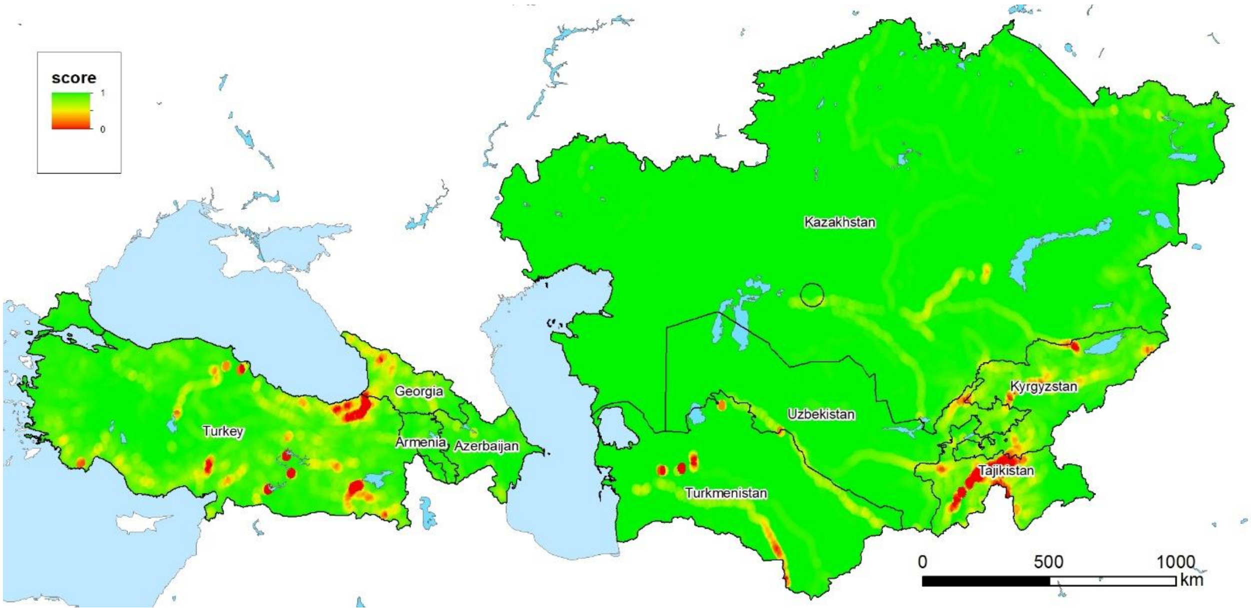
Hydro

The mountains of Central Asia hold an important hydropower potential given by the large height difference and a rich flow coming from precipitation and snow and ice melt. It is estimated that 4% of the world hydropower potential and more than half of Central Asia's potential is clustered in Tajikistan and Kyrgyzstan. Considering that only 5% of it is currently used, there is much space for growth in this sector. Hydro energy represents a cheap source of electricity generation, although the initial investment costs are high and the disruptive impact over the environment can have important consequences.

The hydropower potential data is obtained from (Hoes, Global potential hydropower locations, 2014), (Hoes, Meijer, van der Ent, & van de Giesen, 2017), calculated as points based on the GMTED2010 algorithm using elevation and precipitation data. The dataset contains all potential location points for building hydropower plants (from micro to large ones) worldwide. In order to express the potential in a spatially continuous format, the points were interpolated to create a density map of the potential using the *Point Density* tool (Spatial Analyst extension) in ArcGIS. The electricity production (GWh) was used as *Population* field calculated over a 20 km radius.

The dataset has been further normalised, with the values expressed as a range between zero and one (zero for the lowest and one for the highest value). For the cost map, these values are inverted, the highest potential having the lowest friction score, i.e. zero (**Figure 16**).

Figure 16 - The hydro potential classification in Central Asia



4.4.4 Barriers from natural and anthropic hazards

Natural and man-induced hazards have as consequence the emergence of risk of damage or destruction of the electric infrastructure. Depending on the triggering agent, they have natural causes, mainly determined by the sudden manifestation of geodynamic processes, or human causes, represented largely by armed, political or economic conflicts (which can have ethnic or cultural roots). They jeopardise trans-border cooperation. These hazards can turn into barriers with varying magnitude against building an infrastructure for electricity transmission stretched over several thousands of kilometres crossing multiple countries.

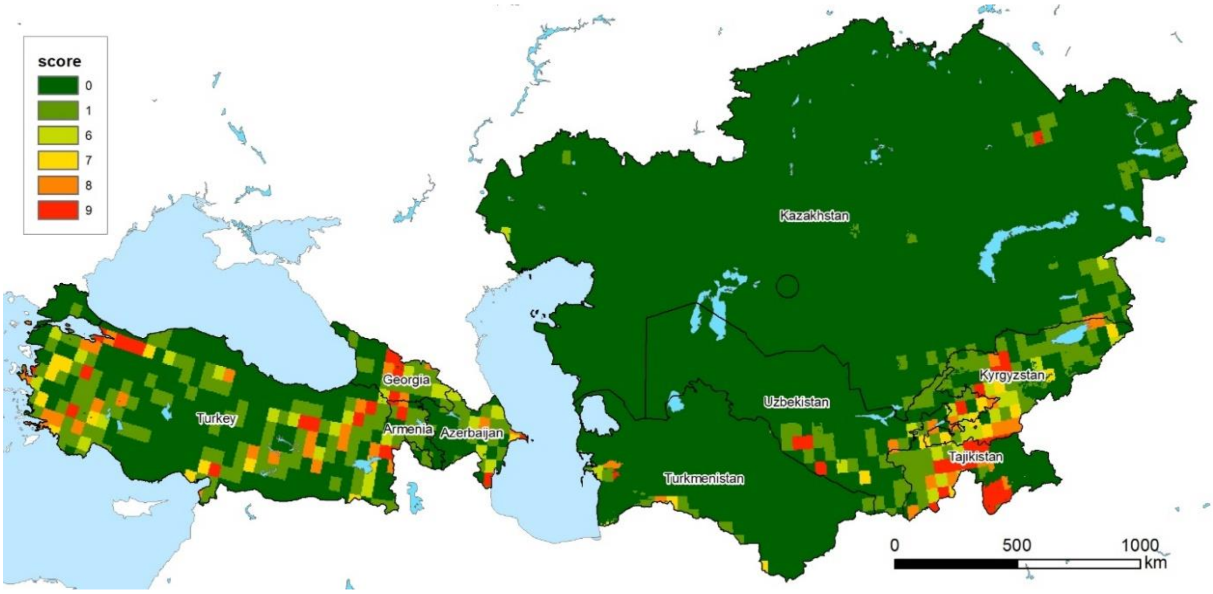
4.4.4.1 Earthquakes

Earthquakes are sudden geodynamic shakes, which can have destructive effects on buildings and infrastructure. They occur generally in areas with a certain tectonic and structural configuration associated with active parts of the earth crust.

The used dataset, compiled in 2005, is by the Columbia University (Center for Hazards and Risk Research - CHRR - Columbia University, and Center for International Earth Science Information Network - CIESIN, 2005) (Dilley, et al., 2005), following a collaboration between the Center for Hazards and Risk Research (CHRR) and the Center for International Earth Science Information Network (CIESIN). The dataset is based on the Advanced National Seismic System (ANSS) Earthquake Catalog data of actual earthquake events exceeding 4.5 on the Richter scale during the period from 1976 to 2002. The dataset's spatial resolution is of 2.5-minute grid (approx. 5 km), which is sufficiently detailed to capture the overall occurrence of the phenomenon. The frequency of an earthquake hazard has been calculated for each grid cell and then the entire set has been classified in deciles that are 10 classes containing approximately the same number of cells. The original classification scheme was retained for this analysis.

From the global dataset only the subset covering the region of interest has been kept. The areas with missing values (No Data) have been assigned a zero value frictional score (the most favourable to crossing) for reasons related to the cost map building algorithm (**Figure 17**).

Figure 17 - Earthquake hazard susceptibility classification in Central Asia



4.4.4.2 Landslides

Landslides are gravitational processes with swift dynamics, which can potentially destroy or damage the buildings on top of the affected terrains. The potential triggering factors lie within a favourable combination of steepness and geology that can be enhanced by the water presence and volume, the overload with buildings and triggering events like earthquakes.

The used dataset, produced in 2005, comes out of a partnership between the Center for Hazards and Risk Research (CHRR) at the Columbia University, the Norwegian Geotechnical Institute (NGI) and the Columbia University Center for International Earth Science and Information Network (CIESIN) (Center for Hazards and Risk Research - CHRR - Columbia University, Center for International Earth Science Information Network - CIESIN - Columbia University, and Norwegian Geotechnical Institute - NGI, 2005) (Dilley, et al., 2005). To assess the hazard, slope, soil, rainfall, seismicity, temperature and soil moisture data have been used. The hazard is classified in nine classes but those from one to four are considered negligible, so only those from five to nine have been maintained for the final dataset. The original classification scheme was retained for this analysis. The dataset spatial resolution is of 2.5-minute grid (approx. 5 km) which is sufficiently detailed to capture the overall occurrence of the phenomenon.

From the global dataset only the subset covering the region of interest has been kept. The areas with missing values (No Data) have been assigned a zero value frictional score (the most favourable to crossing) for reasons related to the cost map building algorithm (**Figure 18**).

Figure 18 - Landslide hazard susceptibility classification in Central Asia

4.4.4.3 Soil erosion

Soil erosion (sometimes termed soil loss) measures the superficial material that is removed by various erosional processes (pluvial, gravitational, wind, agriculture). If this material loss occurs in large quantities and with a fast rate, it can affect the stability of built infrastructure (e.g. the base of the pillars holding the power lines). This problem may be more acute especially in remote and isolated areas where the inspection and maintenance are performed less often. This parameter is included in the analysis to estimate the phenomenon's magnitude and to be able to prevent crossing the areas with high dynamics in this respect.

The dataset comes from the European Soil Data Centre – ESDAC (Panagos, Van Liedekerke, Jones, & Montanarella, 2012) (European Commission, Joint Research Centre, 2019). The soil loss estimation covers 84% of the global surface (125 million km2) using the RUSLE model (Borrelli, et al., 2017). The measurement unit is t ha-1 yr-1. The spatial resolution of the dataset is 25 km, which comes from an original resolution of 250 m. The provided resolution is sufficiently detailed to catch the overall development of the phenomenon.

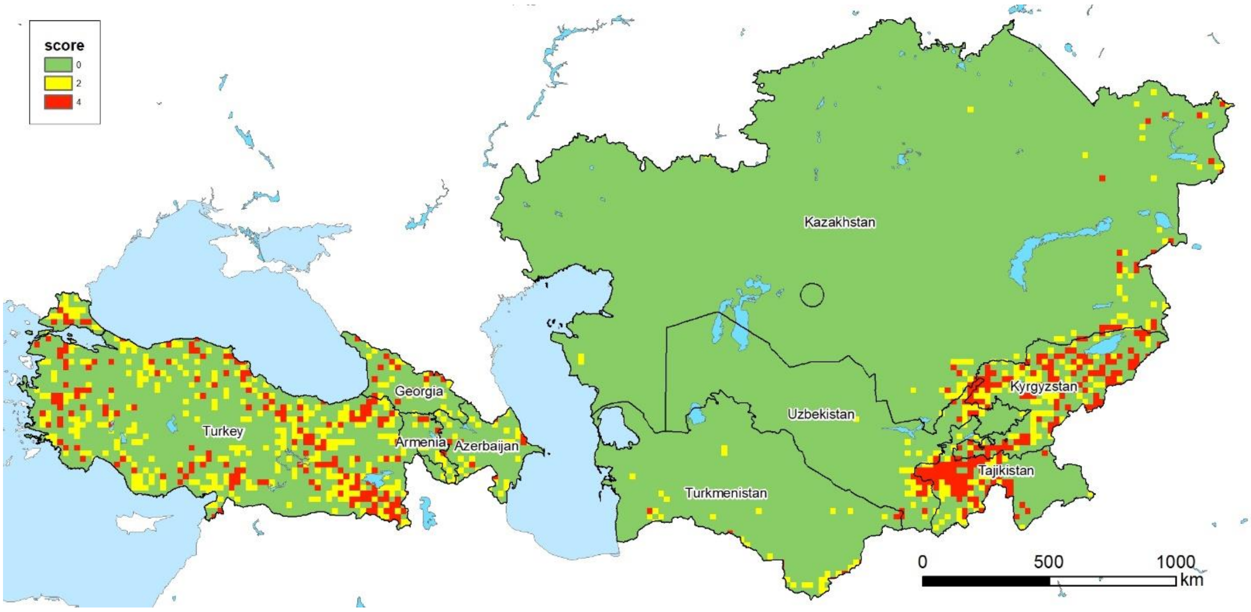
From the global dataset, only the tiles covering the region of interest is kept for this study, with values ranging from zero to 280 t ha-1 yr-1. The dataset values have been reclassified in three cost classes (**Table 7**).

Table 7 - The reclassification of the soil loss values

Original values t ha-1 yr-1	Friction score
0-3	0
3-9	2
9-280	4

The original dataset only includes the areas covered by a soil blanket. The areas without soil cover are excluded from the dataset (i.e. water bodies, deserts and barren lands, rocky areas). In order to prevent the occurrence of No Data values, which are excluded from the cost map and optimal path analysis, dataset was completed by assigning a zero frictional score to these areas (**Figure 19**).

Figure 19 - Soil erosion hazard susceptibility classification in Central Asia



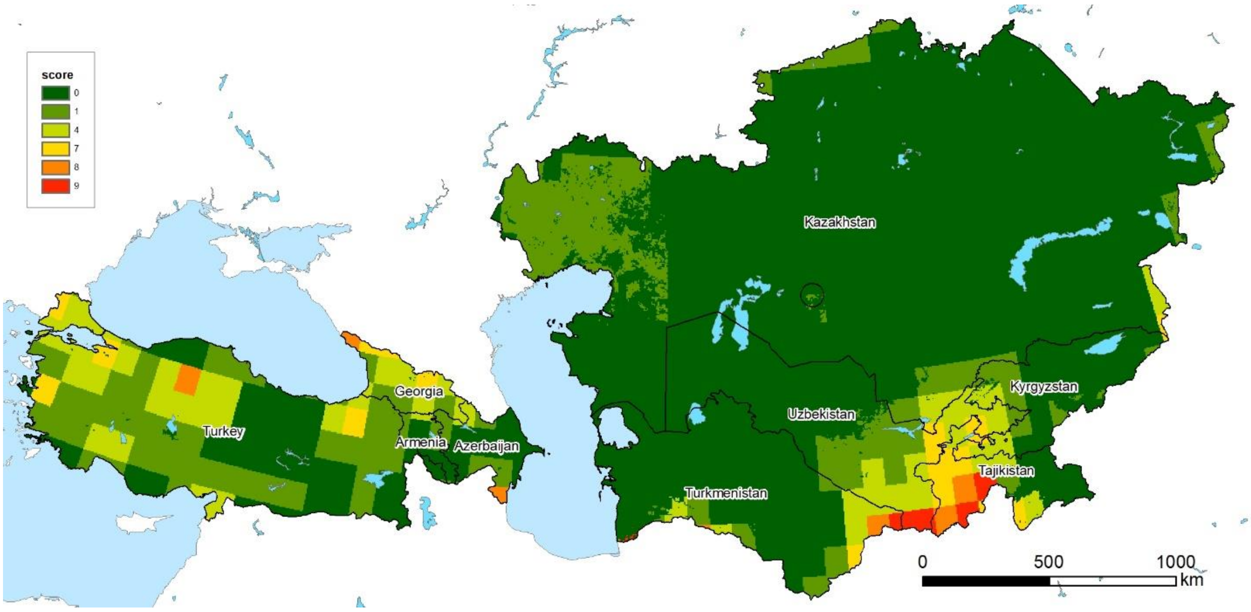
4.4.4.4 Floods

Floods are hydrological manifestations with geodynamic effects (erosion), which may affect the buildings placed in the affected areas. They are episodic events, intermittent, with variable intensity. The affected areas usually occupy the bottom of the valleys or form low-laying ribbons along rivers. The buildings placed on flooding areas may suffer damages or can be thoroughly destroyed, so it is important to consider these areas in the cost analysis.

The used dataset, produced in 2005, is provided by the Columbia University (Center for Hazards and Risk Research - CHRR & Center for International Earth Science Information Network - CIESIN, 2005) (Dilley, et al., 2005) following a collaboration between the Center for Hazards and Risk Research (CHRR) and the Center for International Earth Science Information Network (CIESIN). The dataset documents all major floods that occurred between 1985 and 2003. The frequency of a flood hazard has been calculated for each grid cell and then the entire set has been classified in deciles that are 10 classes containing approximately the same number of cells. The original classification scheme was retained for this analysis. The dataset spatial resolution is of 2.5-minute grid (approx. 5 km), which is sufficiently detailed to capture the overall occurrence of the phenomenon.

From the global dataset only the subset covering the region of interest has been kept. The areas with missing values (No Data) have been assigned a zero value frictional score (the most favourable to crossing) for reasons related to the cost map building algorithm (**Figure 20**).

Figure 20 - Flood hazard classification in Central Asia



4.4.4.5 Armed conflicts

Open military conflicts do not only intentionally or collaterally damage the electric infrastructure (pillars, transmission lines, power substations) but they also negatively affect the investment plans of building and upgrading the infrastructure. Politically disputed areas without open military conflicts suffer similar effects even if the power infrastructure is not actively damaged: investment plans are not followed or are carried out with delays and the incomplete legal frame renders negotiations impossible, which keeps the concerned countries captive in a never-ending linger. Such areas may become an obstacle for building infrastructure; this is why they are included in the analysis.

The used dataset comes from JRC internal resources, more specifically a non-public database on the geopolitical situation in Central Asia with a focus on energy issues. Besides the open military conflicts from the last 20-30 years, the politically disputed areas and the borders between the countries experiencing political or economic disagreements are also considered. Even if some military conflicts are no longer active, the formerly affected regions or countries still suffer from post-war consequences, which translate into a difficult relation with the former enemy, drastically limiting the appetite for economic cooperation. Areas where terrorist attacks or isolated attempts occurred are not considered even if these resulted in damaged power infrastructure.

The conflict areas considered are the following:

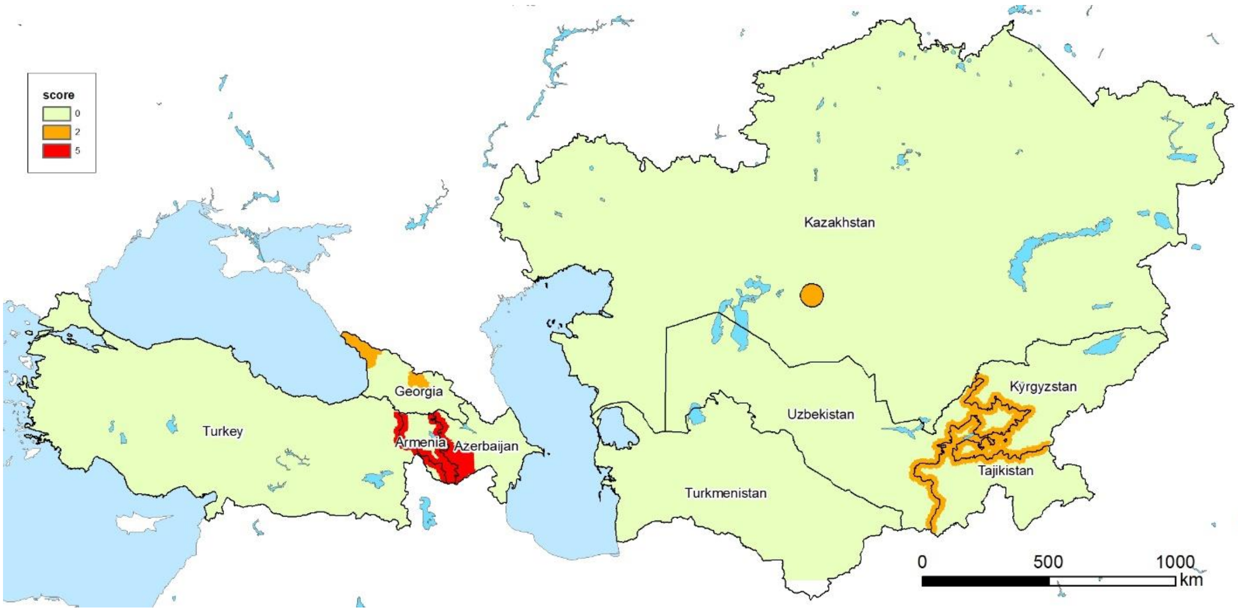
Conflict area	Issue
Abkhazia (Georgia)	Open armed conflict in 1992-1993 following the attempt of Abkhazia to secede from Georgia, to which it belonged. Abkhazia declared its independence, but it is not recognised by the United Nations, being still considered as part of Georgia. The Georgian government has no control over the entity's territory, declaring it as being occupied by the Russian army.
South Ossetia (Georgia)	Open armed conflict in 1991-1992 and 2008 following the attempt of South Ossetia to secede from Georgia, to which it belonged. South Ossetia declared its independence, but it is not recognised by the United Nations, being still considered as part of Georgia. The Georgian government has no control over the entity's territory, declaring it as being occupied by the Russian army.
Nagorno-Karabakh (Azerbaijan)	Open armed conflict from the end of the 1980s until 1994 with periodical resurges until present, following the intent of the autonomous region of Nagorno-Karabakh

Conflict area	Issue
	to secede from Azerbaijan and unite with Armenia. Initially under the Armenian army control, today the region is de facto independent under the name of Artsakh, which is internationally unrecognised. The international community acknowledges it as a part of Azerbaijan. The Azeri government has no control over the entity. The Armenian army still controls approx. 9% of the Azerbaijani territory adjoining the entity.
The border between Armenia and Azerbaijan	As a consequence of the aforementioned conflict, the border between both countries is closed. In such conditions it is hard to see opportunities for cooperation.
The border between Armenia and Turkey	The border between both countries is closed since 1993 as a measure taken by Turkey to drive the withdrawal of Armenian military forces from Azerbaijani occupied territory. This situation is not favourable to any cooperation or joint building projects.
Baikonur (Kazakhstan)	This area, which is leased and administered by Russia (until 2050), is located on the Kazakh territory surrounding the homonym cosmodrome. Although there are no conflicts between both countries regarding the area, the nature of activities developed limits its possible use for energy generation or crossing.
The border between Uzbekistan and Kyrgyzstan	The Uzbek-Kyrgyz border is demarcated on 80% of its length. Starting from 2016 there have been recorded armed incidents along unmarked segments. There are also periodic incidents between Kyrgyzstan and the Uzbek enclaves located on the former's territory.
The border between Uzbekistan and Tajikistan	Following the bombing attempts of 1999 in Tashkent, Uzbekistan has unilaterally decided to mine the border with Tajikistan with the aim of limiting the drug trade and terrorist infiltration. The relations between both countries have improved after 2016 with plans for demining the border.
The border between Kyrgyzstan and Tajikistan	Starting in 2014 there were recorded border conflicts between the two countries on ethnic and economic grounds, which led to closure of several border-crossing points. The tense relations between the two countries keep open the possibility of conflict escalation.

Of course, the present situation should not be considered as immutable in the long term, but the recent development of conflicts impacts at least on the short- and medium-term politic, economic and legal climate, as well as on the international relations in the area.

Conflict-free areas are scored as zero friction. The areas affected by the Armenian-Azeri conflict, i.e. Nagorno-Karabakh, and the borders between Armenia and Azerbaijan and Armenia and Turkey, respectively, received a score of five due to the high risk of escalation or the lack of any perspective for collaboration. The other concerned areas received a score of two, either due to the efforts towards mitigation or due to a rather peripheral location, which might not severely affect a lengthy trans-border transmission line (**Figure 21**).

Figure 21 - The disputed and conflict areas in Central Asia and their classification



4.4.5 Proximity to power infrastructure

Power transmission infrastructure transfers electricity from the place where it is generated - the power plant - to the consumer through substations where voltage is usually stepped down and eventually fed into the distribution grid. Depending on the technology used (AC or DC), power transmission over long distances may imply significant losses due to the lines' impedance (Padiyar, 2011). The length of the transmission lines, which have to be as short as possible, is therefore an important parameter to be taken into consideration during planning. Besides the aforementioned losses, longer lines imply higher costs for the materials needed for their construction (steel and concrete for the pillars, various metallic alloys for the conductors).

As the ultimate scope of the generated electricity is its consumption, the proximity of the substations, which are located close to large urban or industrial electricity consumers, represents an important criterion for routing the power lines.

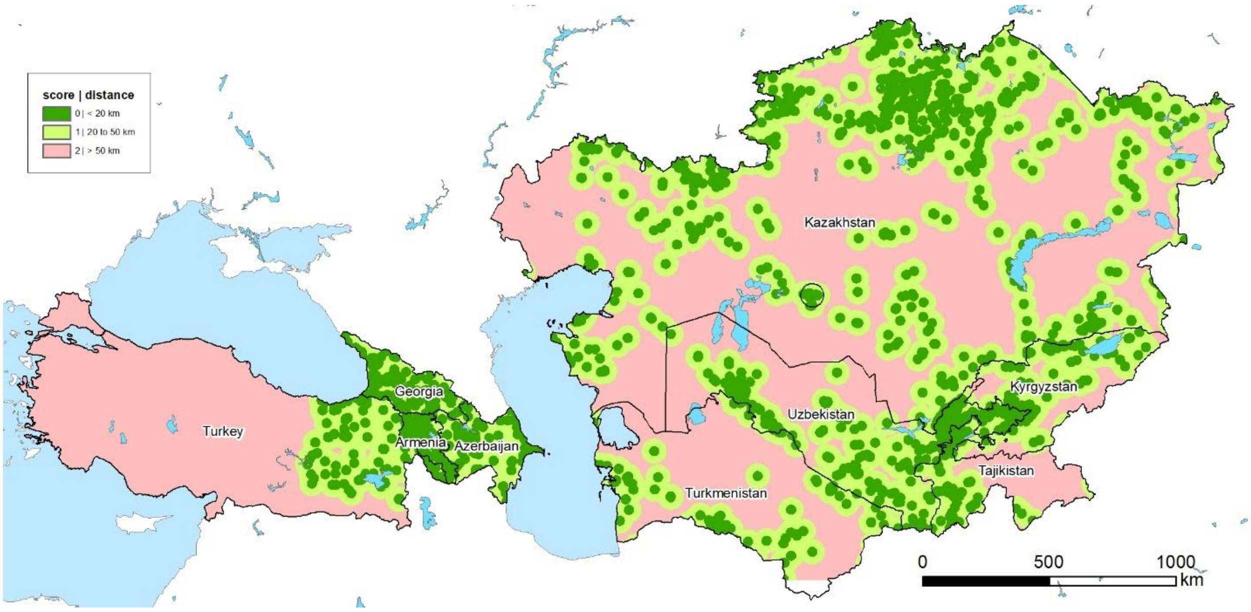
The used datasets originate from the web platform OpenStreetMap (OpenStreetMap, 2019), from which the objects labelled "power station" were extracted within the studied region. OpenStreetMap is an open collaborative project, which aims at creating an editable map of the world. Besides the obvious advantages of such a source (free data, rich and spatially diverse), it also shows several shortcomings. Its main weakness is the lack of uniformity or homogeneity, which is due to the varying efforts of the involved volunteers, mapping certain areas with more detail than others. Consequently, the areas differ regarding their quantity of the geospatial information. Despite these shortcomings, OpenStreetMap proved to be the most appropriate source to locate the power substations of the Central Asian realm. 2376 substations were identified within the five Central Asian countries and three in Transcaucasia. These were subsequently imported in the geospatial satellite imagery service Google Earth, to assess their location accuracy and functionality.

A 20 km radius buffer was generated around the power substations, which is considered the most favourable area to build a crossing transmission line. This is due to the proximity to a linkage with the existing power grid. This area is scored zero for the cost map (**Table 8**). A second buffer with a 50 km radius is built concentrically to the first one. Located at a larger distance from the substation, the connection cost is higher, so the friction score assigned is one. The rest of the areas were assigned a friction score of two (**Figure 22**).

Table 8 - The reclassification of the proximity to the power infrastructure

Buffer zones from substations (km)	Friction score
0-20	0
20-50	1
>50	2

Figure 22 - The distance to power infrastructure in Central Asia



4.4.6 Data processing

The data were retrieved from their respective sources in various formats and characteristics (projection, resolution). To make all datasets compatible and suitable for seamless use in the analysis, a series of processing was performed over the original sets.

First, a suitable projection for the studied region was performed. Due to its large area and its longitudinally elongated shape, the purpose-built projection was based on a modified Asia North Albers Equal Area Conic type (EPSG 102025). Since this type of projection keeps the area unaltered, it is the most appropriate for the type of analysis performed. The datum D_WGS_1984 was used. 57° longitude east was defined as the central meridian and 43° and 50° latitude north as standard parallels, which ensures minimum distortions over the concerned area.

All vector datasets were converted to raster, if this was the case, since this was the final format of the analysis.

The original data came at various spatial resolution: from 90 m for the elevation to 25 km for the soil loss. In order to perform the analysis at the finest scale available, the 90 m resolution has been retained as the basis. All the other datasets were resampled to match this one in order to achieve the same spatial pixel size and as matching the cell alignment (i.e. having the same origin).

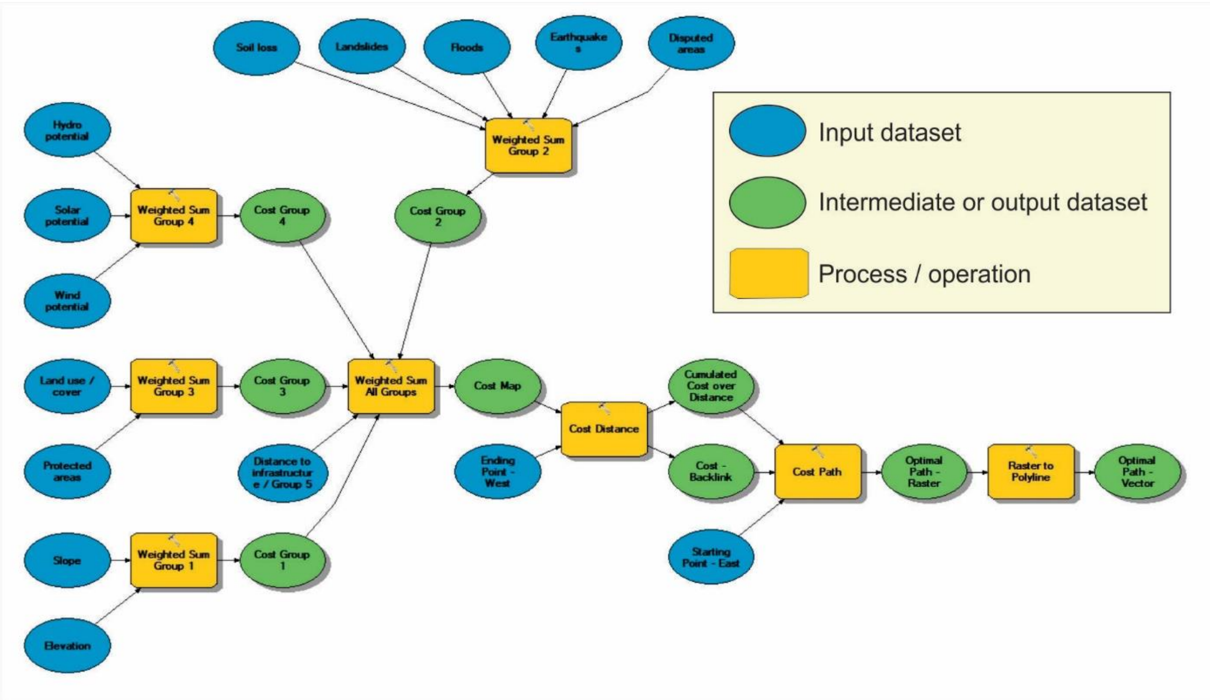
Finally, for all datasets the statistics and pyramids were calculated. This is an internal ArcGIS operation, needed for a better and faster display.

4.5 The model

4.5.1 Structure

The model for the analysis is built using the application ModelBuilder, included in the ArcGIS 10.1 software produced by ESRI (**Figure 23**). Input data consist of the data sets described above, unitary regarding their spatial parameters (format - raster, projection, resolution). In addition, the pixel's value represents the friction score, or the associated cost required to cross it.

Figure 23 - The model used to compute the optimal path



Mainly five functions were used:

- Reclassify – to reclassify the original values of the datasets in classes or friction score (not presented on the diagram in **Figure 23**). A scale of 10 classes is used (from zero to nine), where zero represents the class with the highest favourability (zero resistance to crossing).
- Weighted Sum – to combine the datasets from the same group to obtain a composite cost of crossing. The combination of the datasets is achieved by multiplying each raster with its weight and then summing the included rasters.
- Cost Distance – to generate the map of cumulative cost over the distance from the source placed on the triple-border point (Bulgaria, Greece, and Turkey). The cumulative cost over the distance takes into account the dataset's spatial resolution for each pixel's cost calculation. The cost calculation is done towards all neighbouring pixels, also diagonally. A Backlink raster file is created in order to track back the route towards the source.
- Cost Path – to compute the optimal path from the easternmost terminus back to the source. It uses the results from Cost Distance (cumulative cost map) and the Backlink file.
- Raster to Polyline – to convert the optimal path from raster into vector format, which is more suitable for displaying.
- Although all the aforementioned functions can be individually used, they are assembled into a unitary model (except the Reclassify function), which can be run either function by function, or of one shot, making the operation more efficient.

4.5.2 Grouping and weighting

The datasets chosen for the analysis are grouped into five categories, which are weighted with respect to their composite friction score. In addition, the individual datasets are weighted inside their own group. The resulting model is flexible and can be modified or adjusted according to the request or vision of the user. The groups used are described and explained below.

Terrain parameters

They include elevation and slope. Within the group, the elevation has a weight of 0.6 since its values have more important limitative effects on the building conditions. Slope has weight of 0.4 within the composite score of the group.

Natural and anthropic hazards

The highest weight - 0.3 - is assigned to the earthquakes and landslides due to their larger destructive effects and larger spatial occurrence (in the case of earthquakes). Also, their incidence occurs with a higher degree of uncertainty, which cannot be foreseen with accuracy both for timing and magnitude. Soil erosion and floods each have a weight of 0.1 due to their higher degree of predictability. Areas prone to floods can be intuited even if the timing, frequency and magnitude of the floods cannot be predicted with accuracy. Soil erosion usually occurs with a sufficiently slow speed, so that measures can be taken in order to stop it and to remedy its effects. The disputed areas (armed or political and economic conflicts, borders in litigation) have a weight of 0.2 due to the serious limitations they inflict against developing trans-border projects. On the other hand, their occurrence should be considered as temporary and conjunctural, with the potential to evolve to more favourable conditions for cooperation in the future.

Land use/cover and protected areas

This group includes land use/cover and protected areas. Land use/cover has the highest weight, 0.7, because it also infers the land value, with its associated limitations for building and inherent costs of changing their destination. The protected areas have a weight of 0.3 due to the relatively low impact that high voltage transmission lines have on the crossed terrains (reduced soil footprint, low mobility and without frequent human interventions).

Renewable energy potential (solar, wind, hydro)

The renewable energy potential occupies a crucial role in the analysis given the scope of this study, which aims at a maximum exploitation of this potential. Hence, regions with high RES potential should act as attracting zones for the passage of electricity transmission lines.

Taking into account its importance, the energy potential of all three sources - hydro, solar and wind - is normalised for reclassification within a range from zero (the most favourable, i.e. the lowest friction within the cost maps) to one, given the fact that the potential cannot be negative or unfavourable. It always has a degree of favourability.

For the group's cost map, the weighted average of the constituent potentials is calculated, with solar and wind having each a weight of 0.4 while 0.2 being allocated to hydro. The weight of the solar potential is based on the wealth of the solar resources available in the region as well as to the adequacy of the physio-geographical conditions for installing solar panels over most of the realm's surface. The weight of the wind potential is based on the importance and the amount of the wind resources, and also on the relative easiness to deploy the generating capacities and the flexibility in choosing their location. The lower weight of the hydropower potential is due to the higher impact of hydropower constructions on the environment as well as to their higher initial costs.

Distance to the energy infrastructure

It is not associated with any other dataset and so, it does not form any group.

4.5.3 Cost map and optimal path

Based on the datasets presented above, the cost map is derived, and the least-cost path computed. The composite cost map reflects the constituents, in which the natural characteristics of the terrain take the largest share.

The friction scores largely mimic the natural features, with mountains and water surfaces yielding the highest friction scores. Locally, the human settlements and disputed areas impose their high values to the final map.

Comparing the western Anatolian and Transcaucasian region and the eastern Central Asian realm (**Figure 24**, **Figure 26** and **Figure 27**), one can observe that the former has more areas with high frictional score, while the latter is more favourable to crossing. The two zones are divided by the high-friction-score water basin of the Caspian Sea.

As the mountains in Central Asia occupy a peripheral position, this leaves the central space free of major features that could heighten the friction score, rendering this space highly crossable on most of its surface. The most favourable areas, with a score of under 0.5 overlay, are flat, hazard-free and low-value land use areas in combination with the proximity to existing power substations.

The computed optimal path is issued as a raster file consisting of two values: one for the starting point and three for the cells forming the route. The file is converted into vector format for a better visualisation while keeping only the route cells.

As expected, the optimal path mainly runs across low-friction-score cells (values below one). The several instances with higher scores are due to crossing lengthy linear features like rivers or disputed borders. Generally, the residential areas are avoided with several exceptions owed to local constraints. Moreover, the instances where the path integrates cells with score over three are exceptional, while maintaining its generally straight course.

5 Scenarios and discussions

Three scenarios are proposed. They are detailed below.

5.1 The base scenario

This scenario takes into consideration all the datasets previously discussed. Their clustering, weighting and scoring are detailed in **Table 9**.

Table 9 - The base scenario's composition and weighting

Dataset	Original values	Re-classified values	Intra-group weight	Inter-group weight
Elevation	-999 to 7872	0; 3; 6; 9	0.6	0.2
Slope	0 to 80.32	0; 2; 4; 7; 9	0.4	
Earthquakes	1 to 10	0; 1; 6; 7; 8; 9	0.3	0.15
Landslides	6 to 10	0; 6; 7; 8; 9	0.3	
Erosion/Soil Loss	0 to 280.55	0; 2; 4	0.1	
Floods	1 to 10	0; 1; 4; 7; 8; 9	0.1	
Conflicts	-	0; 2; 5	0.2	
Protected Areas	-	0; 4	0.3	0.35
Land use	37 classes: 10 to 220 / qualitative	0; 1; 2; 3; 9	0.7	
Solar potential	581 to 2027	0 to 1	0.4	0.2
Wind potential	0 to 0.75	0 to 1	0.4	
Hydro potential	8.7e3 to 108e9	0 to 1	0.2	
Substations	-	0; 1; 2	1	0.1

In the base scenario, all layers contribute to assembling the final cost surface. The land use and protected areas have the largest weight, while the weight of the terrain characteristics and RES potential is equal and lower. Together they account for ¾ of the score.

For this scenario, two versions were produced, which only differ by their starting points (i.e. the eastern end). They share the same cost surface map. In the first version (**Figure 24** and **Annex map 1**), the starting point is located at the easternmost extremity of Kazakhstan, close to the border with China, where the low-lying corridor of the Dzungarian Gate connects the two countries. In the second version (**Figure 25** and **Annex map 2**), the starting is point still located at the border with China, close to the developing dry port of Khorgas.

On both sides of the Caspian Sea, two intermediate ending points were defined at locations that minimise the distance between both opposite shores. The path between these two points is presumed to be the shortest and it has not been modelled in this scenario.

Figure 24 - The cost map and the optimal path of the base scenario, version 1 (see **Annex map 1** for higher resolution)

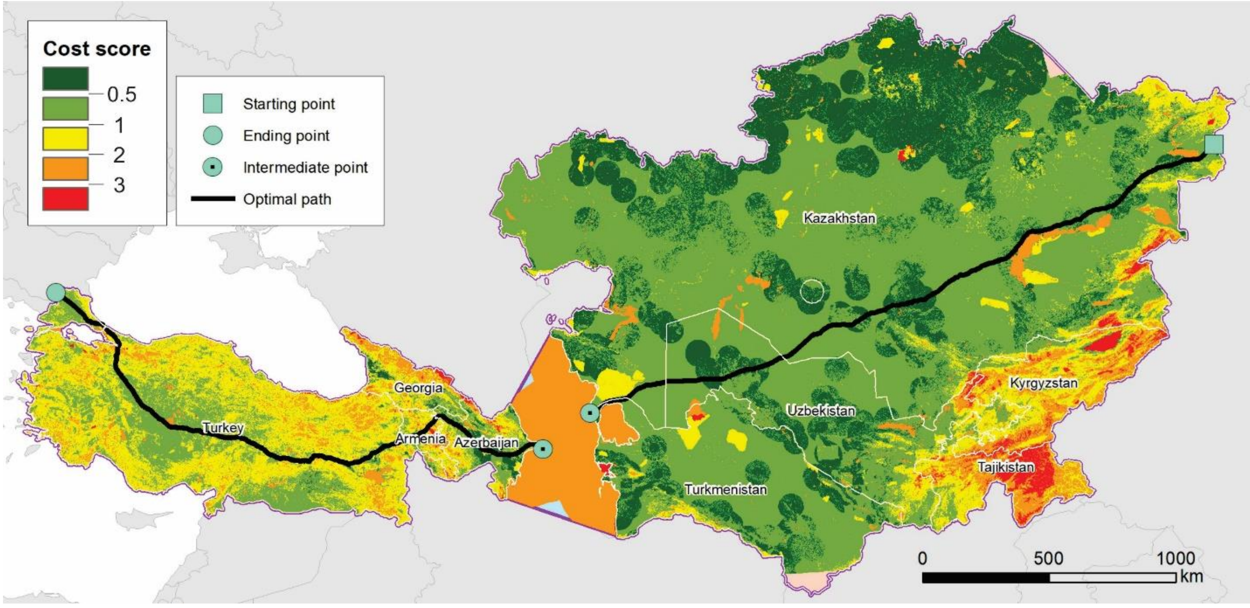
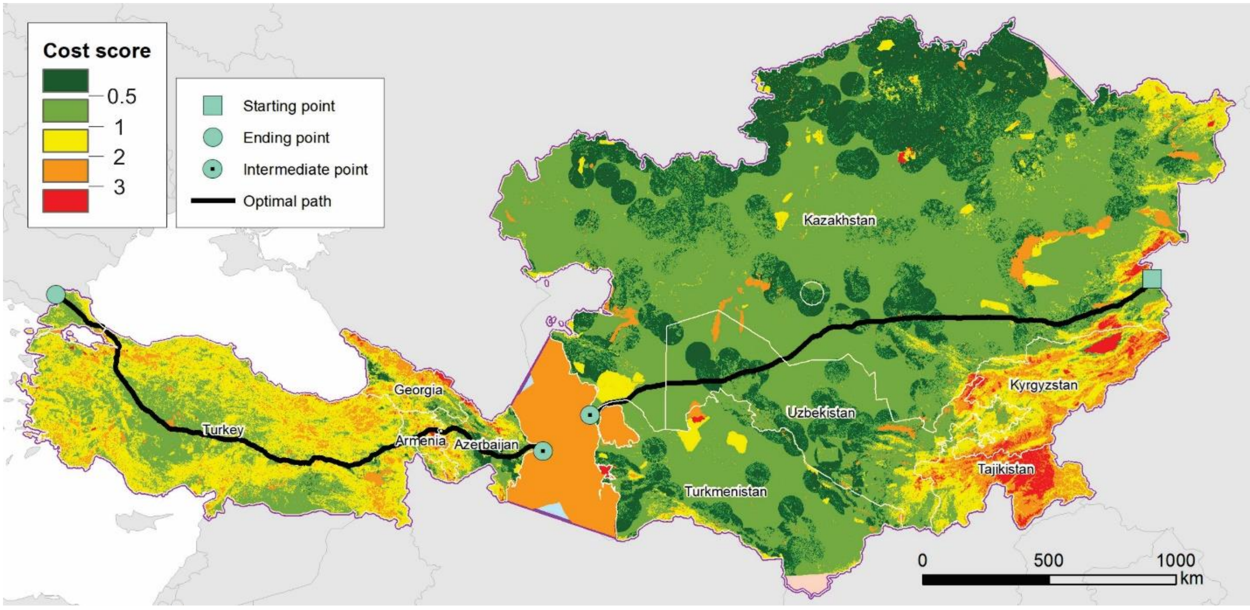


Figure 25 - The cost map and the optimal path of the base scenario, version 2 (see **Annex map 2** for higher resolution)



In both versions the eastern branch of the optimal path has a slightly swaying shape while maintaining its generally straight course toward the intermediate point. The swaying deviations from the straight line are due to presence of water bodies and local land use. It also shows the best trade-off between the different types of RES potential. While the best solar potential is at the southern edges, this southward pull is accommodated by northern locations with significant wind potential. The mountainous areas have the highest hydro potential, but they also have unfavourable friction scores from other variables, like altitude, slope and natural hazards. The optimal path passes through several clustered areas located in the proximity of existing substations, ensuring the link with the existing power infrastructure.

Its western branch, through the Anatolian and Transcaucasian areas, adheres to the same principles of routing. Its southward-bent shape is explained, however, by the southern pull of the higher solar potential mixed with a more homogeneous wind potential. In addition, the northern half of the Anatolian Plateau is more mountainous with steeper slopes, which bends off the route.

The resultant shape of the optimal path is close to a straight line, which minimises its length and reduces the costs. The main advantage of this path is its ability to collect the optimal combination of the RES potential over the shortest distance. It also crosses large, relatively unused flat spaces in Central Asia, which reduces the related costs. However, as such it does not show high connectivity with existing infrastructure, human settlements and developed economic areas. On the other hand, it could trigger the development of the currently unused areas.

The first evaluated path measures 5460 km in length, the second 4990 km. The Caspian Sea crossing of 235 km is to be added, as a straight line between the two intermediate points.

5.2 "No renewables" scenario

In this scenario renewable energy sources do not contribute to the final cost map. The remaining components contribute with different weights to the final weight map (**Table 10**).

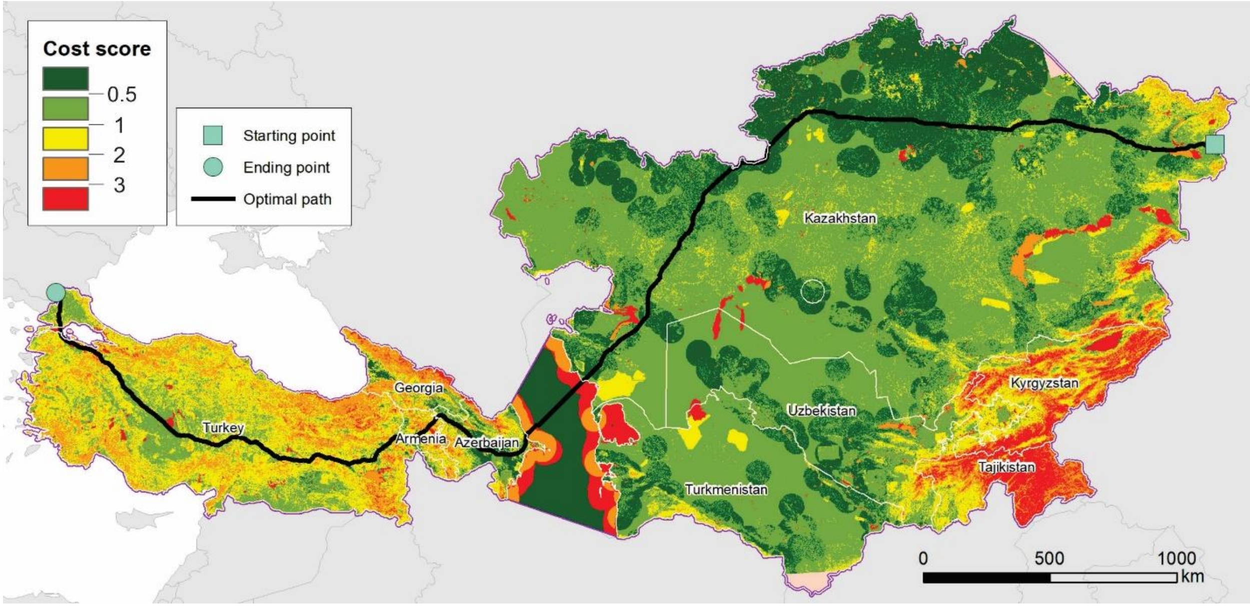
Table 10 - The "no renewables" scenario's composition and weighting

Dataset	Original values	Re-classified values	Intra-group weight	Inter-group weight
Elevation	-999 to 7872	0; 3; 6; 9	0.6	0.3
Slope	0 to 80.32	0; 2; 4; 7; 9	0.4	
Earthquakes	1 to 10	0; 1; 6; 7; 8; 9	0.3	0.15
Landslides	6 to 10	0; 6; 7; 8; 9	0.3	
Erosion/Soil Loss	0 to 280.55	0; 2; 4	0.1	
Floods	1 to 10	0; 1; 4; 7; 8; 9	0.1	
Conflicts	-	0; 2; 5	0.2	
Protected Areas	-	0; 4	0.3	0.45
Land use	37 classes: 10 to 220 / qualitative	0; 1; 2; 3; 9	0.7	
Substations	-	0; 1; 2	1	0.1

This scenario could be also be named "business as usual" since it takes into account the already existing assets. The starting point is located at the easternmost extremity of Kazakhstan, at the western outlet of the Dzungarian Gate, while the ending point is at the common border of Bulgaria, Greece and Turkey. In this scenario, no intermediate points are fixed on the Caspian Sea's shores, allowing the model to cross the sea without constraints.

The resultant cost map (**Figure 26** and **Annex map 3**) is very similar to the ones found under the previous scenario, but with more points and patches of higher friction score towards the middle of the area in Central Asia.

Figure 26 - The cost map and the optimal path of the "no renewables" scenario (see **Annex map 3** for higher resolution)



This distribution of the score values makes the central area less attractive and pushes the optimal path towards the north of Kazakhstan, taking advantage of the lower friction score determined by the almost continuous presence of substations in that zone.

The western branch, through Anatolia and Transcaucasia, roughly follows the same general path as the one in the previous scenario, although somehow swaying more and taking a different path towards the western end.

This route is longer that the one in the previous scenario (both versions): 6160 km. It has however a couple of advantages, e.g. its ability to serve the populated zones located along the route. Parts of the already existing transmission lines or, at least, right-of-ways, could be used for its building. It also approaches the western part of the Kazakh power grid from a more favourable angle, which opens possibilities for its integration with the rest of the national power grid. In its eastern branch, it runs only through Kazakhstan, which reduces the need for trans-border negotiations and agreements.

5.3 "No substations" scenario

The influence of existing infrastructure is excluded in this scenario, while the rest of the groups equally contribute to the final cost map (**Table 11**).

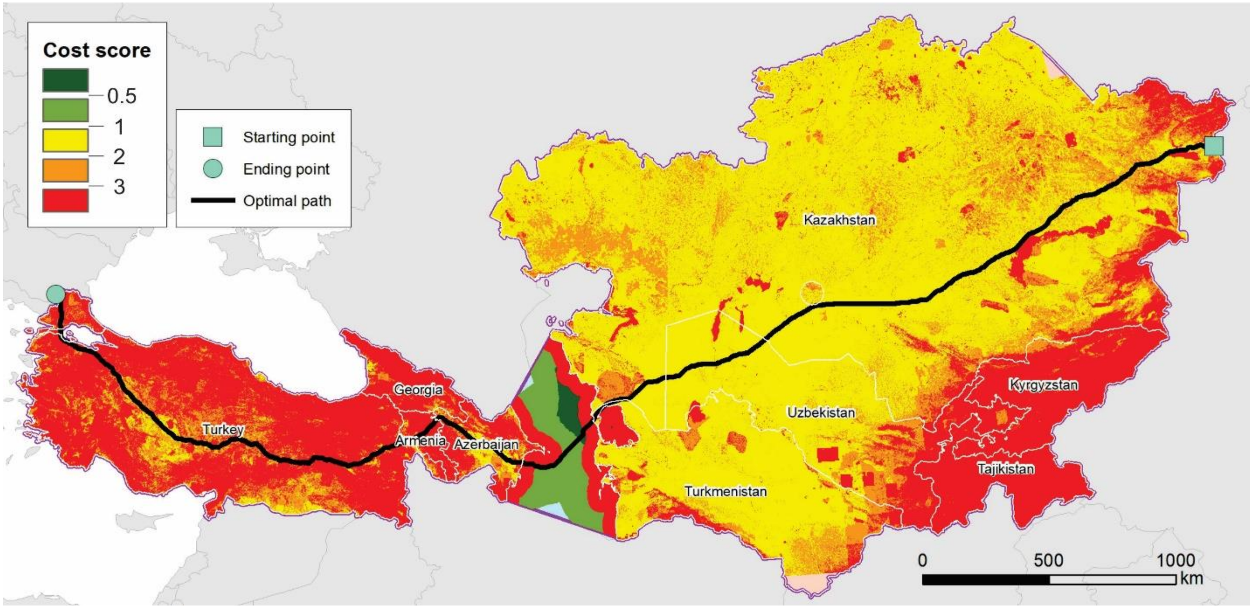
Table 11 - The "no substations" scenario's composition and weighting

Dataset	**Original values**	**Re-classified values**	**Intra-group weight**	Inter-group weight
Elevation	-999 to 7872	0; 3; 6; 9	0.6	0.25
Slope	0 to 80.32	0; 2; 4; 7; 9	0.4	
Earthquakes	1 to 10	0; 1; 6; 7; 8; 9	0.2	0.25
Landslides	6 to 10	0; 6; 7; 8; 9	0.2	
Erosion/Soil Loss	0 to 280.55	0; 2; 4	0.2	
Floods	1 to 10	0; 1; 4; 7; 8; 9	0.2	
Conflicts	-	0; 2; 5	0.2	
Protected Areas	-	0; 4	0.3	0.25

Dataset	**Original values**	**Re-classified values**	**Intra-group weight**	Inter-group weight
Land use	37 classes: 10 to 220 / qualitative	0; 1; 2; 3; 9	0.7	
Solar potential	581 to 2027	0 to 1	0.4	0.25
Wind potential	0 to 0.75	0 to 1	0.4	
Hydro potential	8.7e3 to 108e9	0 to 1	0.2	

This scenario allows a more optimal use of the renewables by ignoring existing infrastructure (proximity of substations). However, terrain parameters, natural and anthropic hazards and land use remain included in the analysis. The equal weight of the groups produces a cost score map with different values, which are higher than in both previous scenarios. However, the resultant optimal path is very similar to the one of the first scenario (**Figure 27** and **Annex map 4**). The starting and ending points are kept at the easternmost extremity of Kazakhstan and the common border point of Bulgaria, Greece and Turkey, with no intermediate points on the Caspian Sea's shores.

Figure 27 - The cost map and the optimal path of the "no substations" scenario (see **Annex map 4** for higher resolution)



Minor differences with the first scenario are due to the obvious opportunity to collect the optimal combination of the RES potential along the route. The small undulations, which are apparent, are due to local land use characteristics. The route is longer than the ones of the first scenario: 5810 km. It crosses the Caspian Sea in the close vicinity of the intermediate points defined in the first scenario. As with the first scenario, advantages include reduced building costs due to the large flat unused spaces crossed in central Kazakhstan, with opportunities for the development of these areas.

6 Conclusions

The continuous and ever-growing need for electricity will require additional high voltage transmission lines as the location of energy resources rarely coincides with the consumption centres. Equally, the growing electricity markets, the need of security of supply, as well as the trend of integrating RES in the power system are driving factors.

Building a transmission line is a matter of choosing the optimal route, which creates the best trade-off between its length (and the associated losses) and the required connections with energy resources and load centres.

As transmission lines are built in the real world, real factors must be taken into account, i.e. the ones that shape the environment and that are themselves affected by the future line.

The factors involved can be of natural, economic, environmental, societal and regulatory nature. Across the territory, the appropriateness of building transmission lines varies from place to place, even involving barriers that are impossible to cross. The number of factors considered can vary according to the scope and scale of the study.

Models must be conceived combining all the factors to offer an appropriate image of the environment, in which the construction is envisaged.

Accordingly, in current study a model was developed for computing the optimal cost path based on a set of selected factors. This model was applied to the Central Asian countries with the aim of building a power interconnection, which allows electricity transmission towards Europe via Transcaucasia and Turkey. GIS software was used for this purpose as this tool offers an effective way of finding the best route through a cost map that includes a selected number of variables combined in a specific way.

Building the cost map, which depicts the easiness with which a surface is crossed, was accomplished by bringing into the analysis the relevant factors that influence the path of the transmission line. Five categories of factors were used, consistent with previous work on the subject: terrain parameters, natural and anthropic hazards, land use and protected areas, RES potential and distance to existing power infrastructure (i.e. substations). Subsequently the optimal cost path was computed, i.e. the shortest path between fixed starting and ending points with the lowest cumulated cost.

Three scenarios were modelled: (1) the "base" scenario (two versions), (2) the "no renewables" scenario and (3) the "no substations" scenario.

The shortest route was found for the "base" scenario, which considers all factors: 5460 km (version one) and 4990 km (version two).

The cost maps of scenarios (1) and (3) were very similar and so were the resulting optimal paths, while scenario (2) lead to a different outcome, i.e. a longer and less straight route.

Hence, the main conclusion of this exercise is that the RES potential is the controlling factor in the overall base-scenario path, rather than the proximity to existing power infrastructure. In fact, adding the region's full RES potential to the "business as usual" scenario shortens the optimal path, resulting in lower construction costs and less electricity transmission losses. Moreover, the inclusion of the RES potential leads the optimal path through currently unused areas, offering opportunities for their development.

The model presented in this study can be customised by changing the number of factors, the way of combining them and their weight in the final cost map. As such it is a flexible and valuable tool that can be used in policy-underpinning studies in the context of strategies aiming at enhanced electricity connectivity with Central Asia.

Furthermore, this model can be applied to other areas as well since all datasets are publicly available and have worldwide coverage (except *Conflicts*, which has been purposely built for this study, but which can be replicated for the targeted area).

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List of abbreviations and definitions

BRI	Belt and Road Initiative
CAPS	Central Asian Power System
EAEU	Eurasian Economic Union
EC	European Commission
EU	European Union
EU HR	European Union High Representative
GIS	Geographical Information System
kWh	Kilowatts hour
kWp	Kilowatts peak
MS	Member States
MW	Megawatts
PCI	Project of Common Interest
PV	Photovoltaic
RES	Renewable Energy Sources
TWh	Terawatts hour
US	United States
USSR	Union of Soviet Socialist Republics

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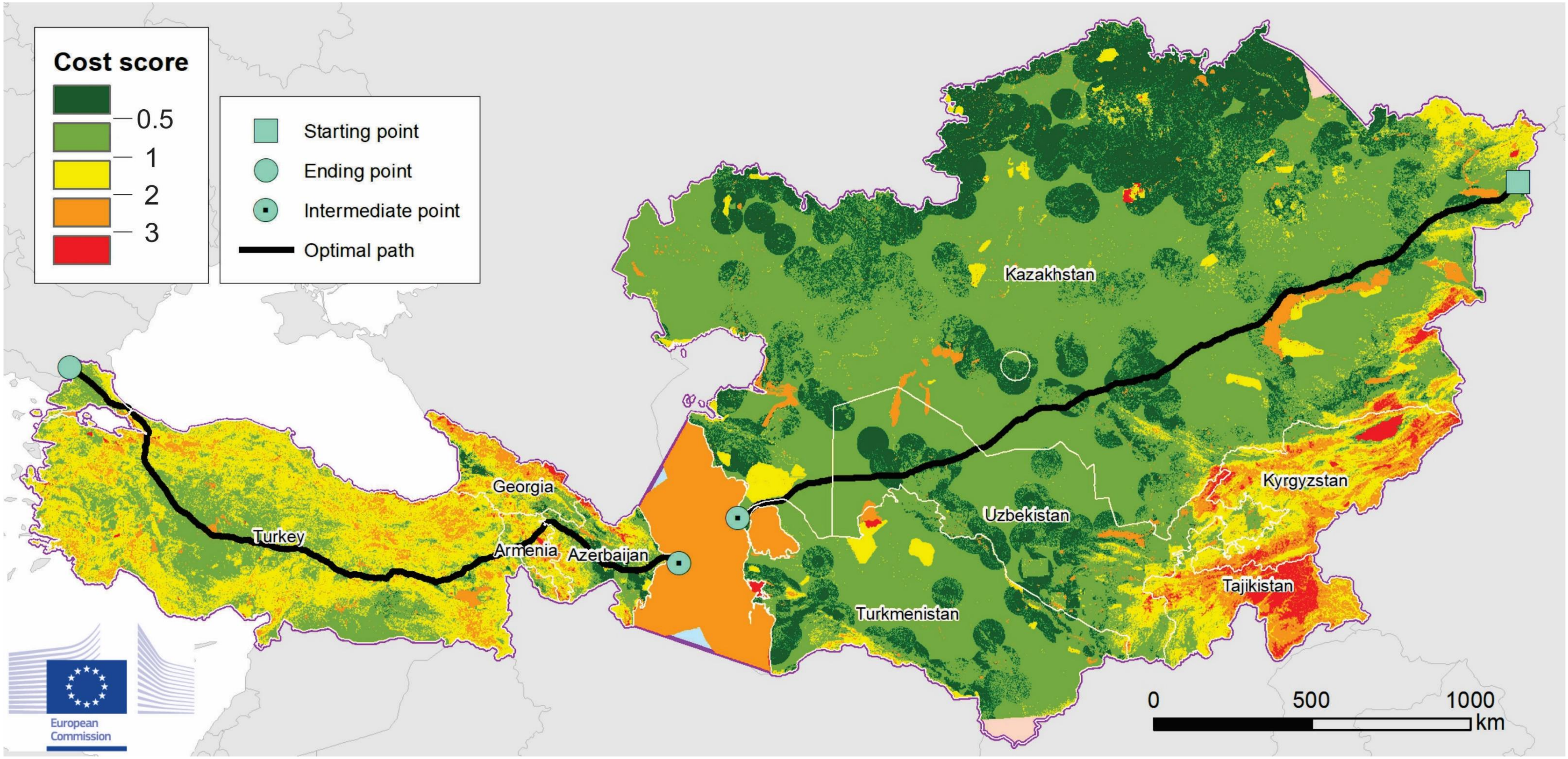
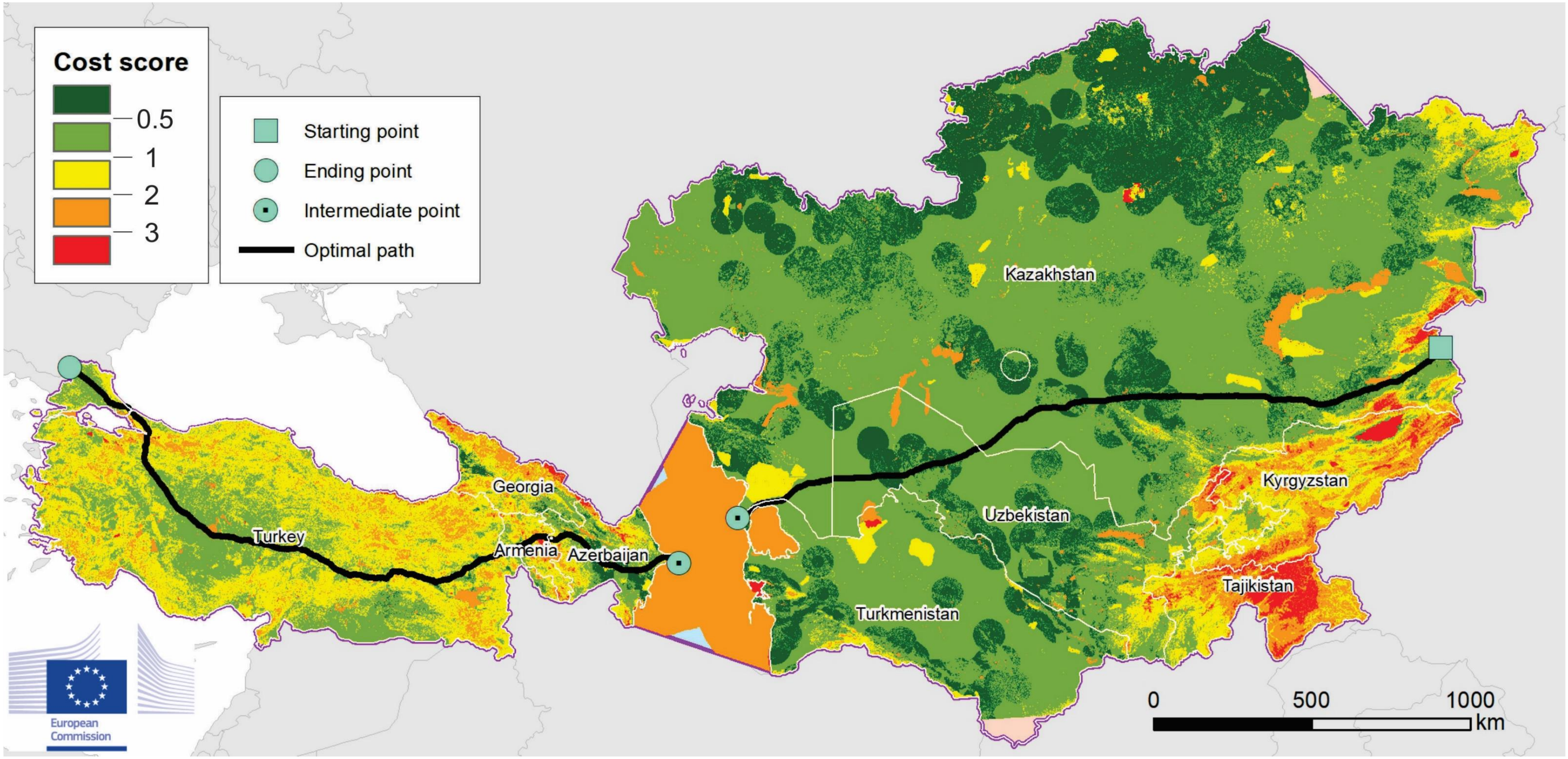
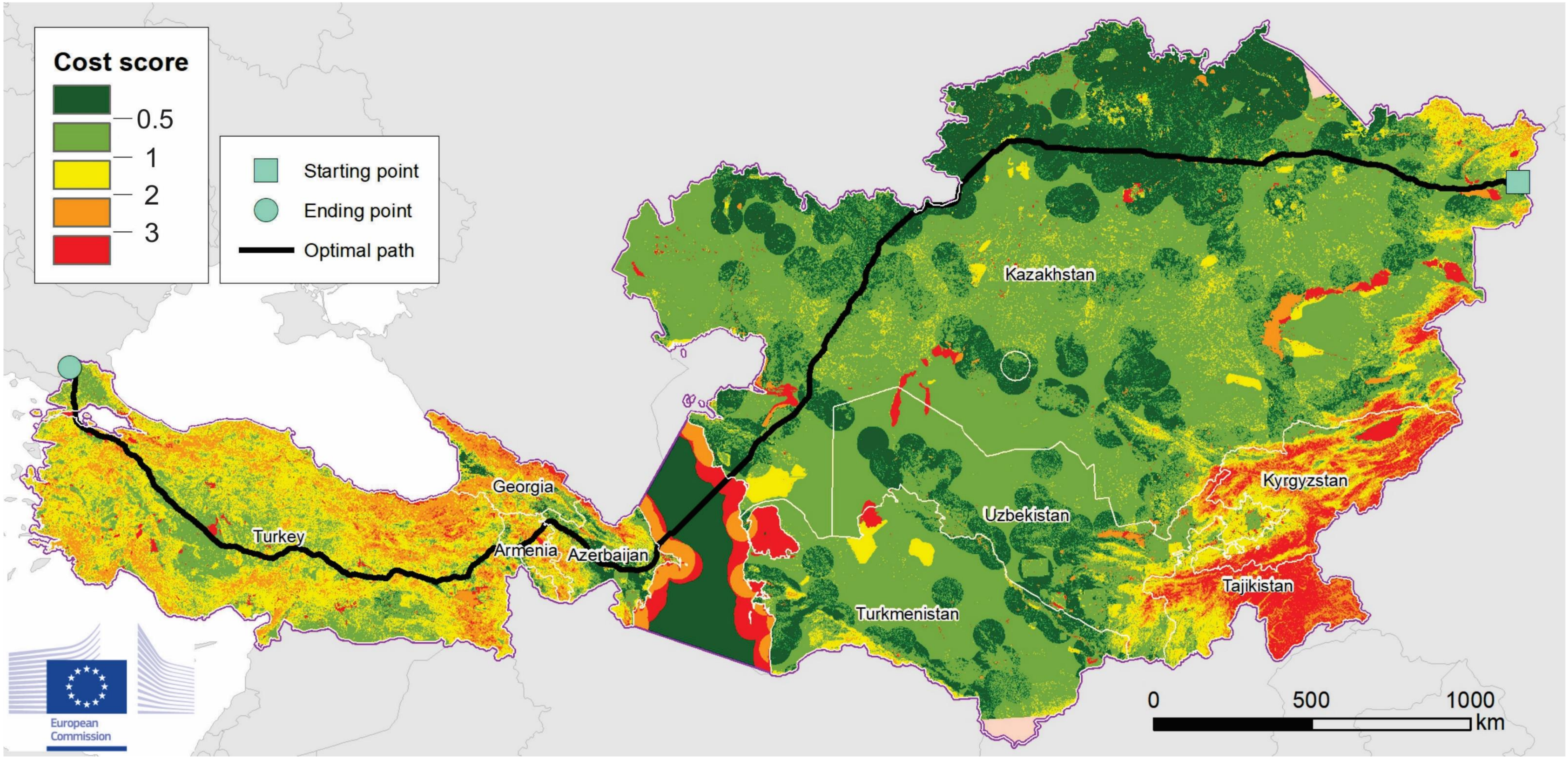


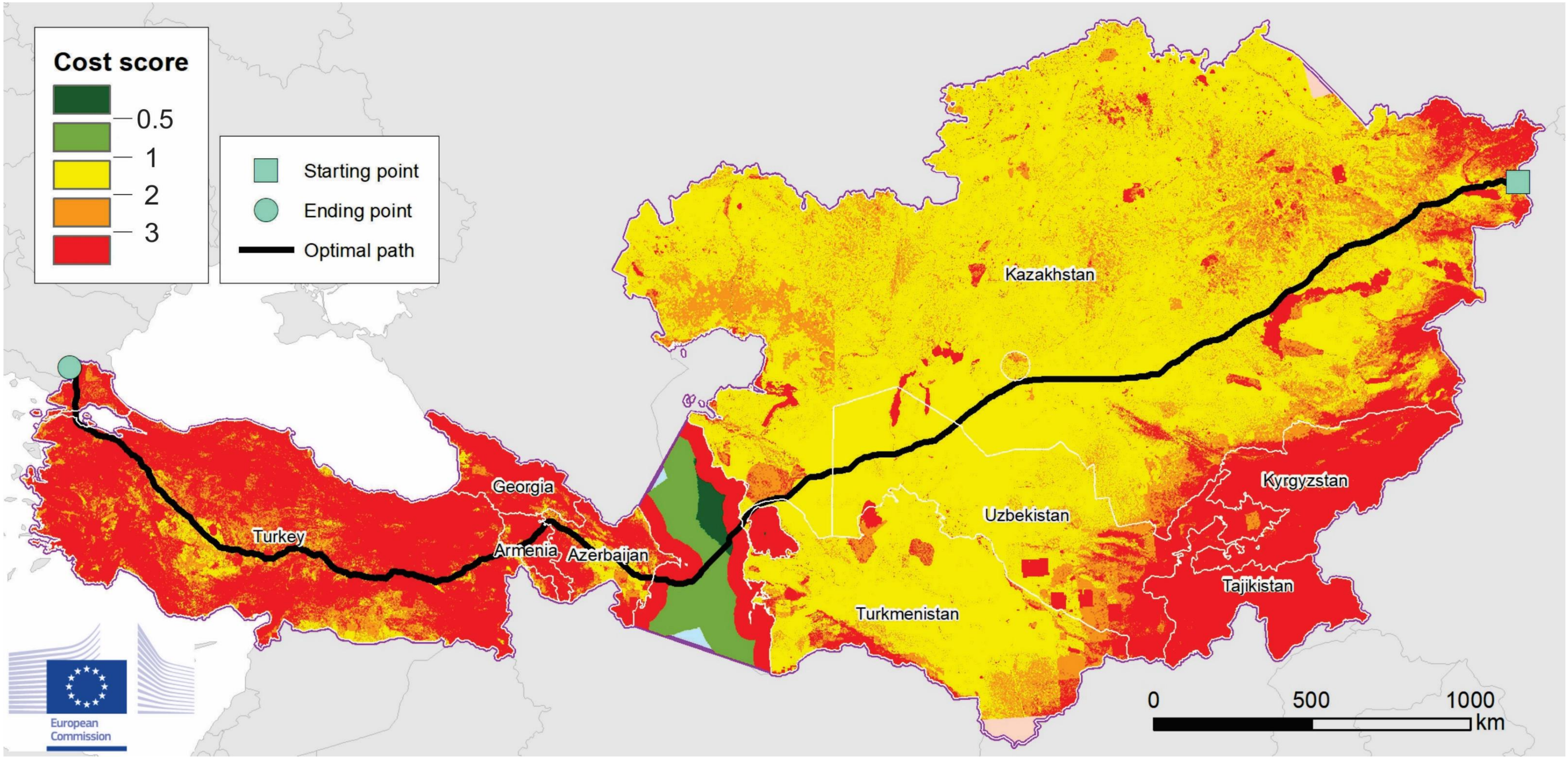
Annex map 2 - The cost map and the optimal path of the base scenario, version 2 (high resolution)



Annex map 3 - The cost map and the optimal path of the "no renewables" scenario (high resolution)



Annex map 4 - The cost map and the optimal path of the "no substations" scenario (high resolution)



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