

Received:
9 August 2016
Revised:
21 December 2016
Accepted:
27 March 2017

Cite as: Aidyn Bakdolotov,
Rocco De Miglio,
Yerbol Akhmetbekov,
Kanat Baigarin. Techno-
economic modelling to
strategize energy exports in the
Central Asian Caspian region.
Heliyon 3 (2017) e00283.
doi: [10.1016/j.heliyon.2017.e00283](https://doi.org/10.1016/j.heliyon.2017.e00283)



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Techno-economic modelling to strategize energy exports in the Central Asian Caspian region

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Abstract

This paper studies the concept of energy security from export-oriented countries' point of view. It aims to test the effects of long-term energy export strategies in the Central Asian Caspian (CAC) region, by exploring the trade-offs between a "risk" indicator and some key variables of the energy system such as the total cost, the quantities exported, and the corresponding revenues. Risk reduction goals are combined with securing a minimum level of revenues from the hydrocarbon exports goals. It is also attempted to provide a definition and a quantification of a risk indicator on the basis of four components.

The analysis makes use of a techno-economic energy system model to quantitatively evaluate the response of the energy sector to energy security risks, and its sensitivity to different export strategies.

Keywords: Energy, Economics, Environmental science

1. Introduction

It is likely that all energy-importing countries are familiar with the concept of energy security nowadays, at least with the definition suggested by the IEA: "*the uninterrupted physical availability at a price which is affordable, while respecting environment concerns*" [1]. Such a definition has the merit to emphasize the

importance of appropriate and timely investments in the supply chain, the links with the environmental issues and the economic development, and the simultaneous short-term and long-term nature, but it still remains clearly “importers-oriented”. Winzer, while conceptualizing energy security, found that the all energy security definitions found in literature are related to continuity of and risks to the energy supply chain [2]. Energy policy of many countries considers security of supply as an important goal. For example, the security of energy supply is one of the three pillars of the energy policy of European Union [3, 4].

At the same time, the international community has started to look at the energy security as a two-sides coin, as energy-importing countries want security of supply from energy exporting countries as well as energy-exporting countries want security of energy demand in energy importing countries [5].

Yergin, in his work on ensuring energy security [6], states that while energy-importing countries (developed world) view the energy security as “the availability of sufficient supplies at affordable prices”, energy-exporting countries focus on security for their exports, “which after all generate the overwhelming share of their government revenues”. The report of Energy Charter (2015) [7] introduces different views and meanings of energy security for energy exporting, transit, and importing countries, in particular between exporters and importers. The report concludes that while “The tools to ensure a security of supply are manifold and include trade, diversification, supply expansion, security enhancement, stockpiling, demand control and, to some extent, energy subsidies”, the concept of security of demand by the energy exporting countries has not evolved yet. The same holds for transit countries, which have not developed any specific concept of energy security and would rather adopt the concept of security of supply.

A very comprehensive analysis of the differences between “classic” and “contemporary” energy security studies has been recently undertaken by Cherp and Jewell [8]. Authors examine the different concepts of the instance, and its evolving history [9], by looking at the four “As” of energy security (availability, affordability, accessibility and acceptability) [10], [11], and discuss whether this approach and related literature address with the key security questions (Security for whom? Security for which values? Security from what threats?). They conclude their study by proposing an alternative concept of energy security as “low vulnerability of vital energy systems”, a definition reflecting not only objective properties of energy stocks, flows, infrastructure, markets and prices, but also political concerns rooted in institutional interests, and that allows for exploration of vulnerabilities with respect to the “exposure to risks” (with different meanings in different context and for different players), as well as to the links between the so-called vital energy systems (e.g. energy services [12], and energy export revenues [13]) and their critical social functions.

Having this latter concept in mind, it is also well known that almost all the most important energy-producing countries are highly dependent on energy exports, and this dependence typically results in a very large share of the energy sector to the GDP and fundamental (critical) contributions to the State budgets.

This is also true for Central Asia and Caspian region countries, Azerbaijan (AZJ), Kazakhstan (KZK), Turkmenistan (TKM), and Uzbekistan (UZB), which are under research focus in this work. These countries are rich in natural gas and oil and their rent share in GDP is quite large (see Table 1).

To develop domestic economies, to commit to environmental targets, and to exploit the fields, energy producing countries need *certain and predictable flows (demand) and fair prices*, and need to include the concept of vulnerability (in terms of “security of demand”) in their energy sector strategies.

In this work, a comprehensive concept of “energy security” for the Central Asian and Caspian Countries has been adopted, based on the following paradigms: ensuring secure transportation of oil and gas to the market through multiple pipeline network in geopolitical cooperation among producers and transit countries of the area, keeping a sufficient willingness to invest in the energy sector, and reducing the risk of export concentration.

Table 1. Azerbaijan, Kazakhstan, Turkmenistan and Uzbekistan: energy resources and indicators.

Indicators	References	AZJ	KZK	TKM	UZB	Sum	China +India	World
CRUDE OIL (%)								
Oil rents (+) (% GDP) (&)	[14]	34-62	26-37	16-41	3-10	–	–	–
Ultimate recoverable resources (Billion of bbl)	[15]	15	71	19	3	108	57	3000
Reserves (Billion of bbl)	[15],[16],[17]	7	35(*)	0.6(a)	0.6	43(*)	35	1480
Domestic consumption (2009, million of bbl/a)	[18]	70.8	118	60.0	21.6	270	3770	30950
Net export (2009, million of bbl/a)	[18]	317	449	14.4	-	780	–	0
NATURAL GAS								
Natural gas rents (+) (% GDP) (&)	[14]	3-12	2-8(^)	22-85	15-91	–	–	–
Ultimate recoverable resources (Tcm)	[15]	4.5	7.2	11.8	3.4	26.9	9.4	425
Reserves (Tcm)	[15]	>0.85	>3.5	>7.4	>1.8	>13.5	3.1	180
Domestic consumption (2009, in Bcm/a)	[18]	10.4	20.3	18.0	43.8	92.5	120	3114
Net export (2009, in Bcm/a)	[18]	5.8	6.9	19.1	12.7	44.5	–	0

(%) Domestic consumption and net export refer only to crude oil; if oil products are added, both values are similar to the values shown in the following tables; (+) as defined in the WB data base, rents are the difference between the value of oil/natural gas production at world prices and total costs of production; (&) 2000–2011 range; (*) average over the range 30–40 B.bbl found in the literature; (a) plus 1.1 B.bbl of proved plus probable reserves in the Caspian Sea [19].

1.1. A concept of energy security in terms of risk considerations

Until recently, about 80% of the Kazakh export passed through the Russian Federation (via Novorossiysk or Samara). Export of Kazakh oil to China started only in 2006, but with relatively small flows due to capacity limitations in Kazakhstan, whereas only Azerbaijan exports significant amount of oil (through the 1.2 Mbb/d Baku-Tbilisi-Ceyhan pipeline) directly to the Mediterranean market. Export of Central Asia's gas is even more concentrated. About 90% of the total export of the area went through Russia until 2009, mainly via the Central Asia – Centre pipeline system crossing Turkmenistan, Uzbekistan and Kazakhstan (CAC pipeline), with a combined capacity of 40 Bcm/a. Azerbaijan is the only country in the area that can export natural gas directly to the Mediterranean Area, through Turkey via the Baku-Tbilisi-Erzurum (BTE), up to a maximum volume of 6.5 Bcm/a. Only after 2012, the Central Asia–China gas pipeline started bringing Central Asian natural gas to the East, highlighting China's interest for Central Asian energy resources. The natural gas through this pipeline is mainly from Turkmenistan, however, some amounts from transit countries are added to the export via the Central Asia China corridor.

Four dimensions have been identified as “key” criteria in the energy export strategy planning: one non-energy related geopolitical/socioeconomic component, and three energy-related factors such as the energy market liquidity, the estimate of energy self-sufficiency and the expectation about energy/environmental policies of the potential customers. Energy related factors have been estimated, only taking into account oil and gas, which are the main energy exporting resources in the CAC area.

A formal representation of the composite risk parameter (1), based on four multiplicative components, is reported hereinafter. Risk is seen from the perspective of the whole exporting Area (four countries), and is meant to influence the willingness to invest in certain new-future energy infrastructures and the delivery of oil and gas to certain markets.

$$RISK = R_C * e^{\left(1 - \frac{1}{R_f}\right)} * \left(1 - \frac{P}{R}\right) * \frac{PES2010}{PES2040} \quad (1)$$

R_C : risk of the destination Country (or market), and of the transit Countries (due to political instability, terrorism, uncertain regulatory framework and rules of law, etc.). It aims to assign a “score” and define a “merit order” among the potential customers in terms of “reliability” and “easiness of business”. The higher is the component, the greater is the overall risk. It ranges from 0 to 100.

$e^{\left(1-\frac{1}{R_f}\right)}$: where R_f is the ratio between the global primary energy supply and the primary energy supply of the consumer¹ ($R_f > 1$). It aims to represent a market liquidity indicator.

The country-size effect can be approximated making use of the parameter, R_f . Such a ratio (higher than 1 by construction) has a negative correlation with the exporter's energy security.

Thus, potential importers with a relatively small share of world consumption (i.e. very high R_f) will be seen as "risky" buyers, whereas other importers whose withdrawals from the available world supply is significant, will have their market risk scaled down (from the point of view of the exporters) to simulate their higher difficulty in replacing the supply coming from the exporting Central Asia Caspian area. The smaller is the importing country's draw on the market, the easier it is for the country to switch suppliers and the higher is supposed to be the corresponding risk of the exporter.

Furthermore, the component $e^{\left(1-\frac{1}{R_f}\right)}$ can never contribute to the "reduction" of the risk (as it is always greater than 1). It is a "short-term" risk component, aiming at correcting the non-energy related risk (R_C): the higher is such value, the higher is the overall risk.

$\left(1 - \frac{P}{R}\right)$: it aims to include the domestic potential of the importing Country. Such a potential is estimated by looking at the expected degree of "domestic exploitation" of the reserves (R) of each potential customer, based on the existing (short-term) trends of domestic production (P). It has been chosen instead of a more standard reserves-to-consumption (C/R) index, as the consumption has been already considered in the market liquidity component.

As P/R is always lower than 1, $(1-P/R)$ falls in the range between 0 and 1. It shrinks the overall risk in case of expected high level of R/P (self-sufficiency).

$\frac{PES_{2010}}{PES_{2040}}$: it aims to capture the efficiency and environmental commitments/policies of the potential customers, and their corresponding expected energy hunger in the future (their willingness to pay for energy). Here, PES is a primary energy supply, and for 2010, PES2010 values are obtained from website of International Energy Agency (IEA), which has a database for most of energy indicators for all countries. For future years, PES2040 values are obtained from different sources [20, 21 and 22].

Such a factor is lower than 1 when the expected future primary energy supply is lower than the current value, and greater than 1 in case of higher future

¹ Market of destination of the exports.

consumption. It corrects the overall risk, and represents a “long-term” component of the overall indicator. The larger is this factor, the higher is the overall risk.

2. Methodology

This study aims to test the effects of long-term energy export strategies on the energy system of the Central Asian Caspian Countries (Azerbaijan, Kazakhstan, Turkmenistan and Uzbekistan), by exploring the trade-off curves between an overall “risk” indicator and the outcomes of key variables of the energy system, such as the cost, the quantities exported and the corresponding revenues.

The analysis makes use of an energy system model, a risk-adjusted concept of diversification, scenario analysis, and trade-off curves to quantify and unveil:

- the endogenous levels of export to the rest of the world (through different directions, driven by the prices that customers are supposed to be willing to pay in the medium-long term);
- the impact of different diversification targets on the key energy-economic variables;
- the impact of diversification targets when combined with minimum revenues strategies.

The following paragraphs provide a description of the “tools”, and present the most interesting trade-offs and results of the analysis.

2.1. The TIMES-CAC-4R

The integrated bottom-up partial-equilibrium energy system model of the Central Asian Caspian Area, titled TIMES-CAC-4R², assembles the 4 separate but structurally-consistent single-region TIMES country models of Azerbaijan, Kazakhstan, Turkmenistan, Uzbekistan by interconnecting them through the representation of energy flows and/or emission permits exchanges. The key-components of the single-regions national TIMES models are the technologies for the production of primary and secondary commodities (mining processes, power plants, refineries, etc.) together with the most representative appliances and devices of the demand sectors (boilers, lighting bulbs, road vehicles, etc.). The energy system development of each model region is driven by a set of demands for energy services in all sectors: agriculture, residential, commercial, industry, and transportation.

²Built using the TIMES model generator developed by the Energy Technology Systems Analysis Program of the International Energy Agency [23]. The model TIMES-CAC-4R has 5981 processes delivering 2464 commodities under 167 user constraints, which describe the energy systems of all 4 regions with 94510 data values.

The model computes a dynamic inter-temporal partial equilibrium for the regional energy and emission markets based on the maximization of total surplus, defined as the sum of surplus of the suppliers and consumers. In other words, it is assumed that the system evolves, while maintaining intra-temporal and inter-temporal partial economic equilibrium, and always occupies the technical possibility frontier. The process of solving the model determines the optimal mix of technologies (capacity and activity) and fuels at each period, the associated emissions, the mining and “trading activities”, the quantity and prices of all commodities, all in time series from the base year to the time horizon of the model.

In the framework of this research, the model was developed and used to assess the dynamics of the energy system of the regions, when energy export levels are driven by the prices that different customers are supposed to be willing to pay³.

The model responds to economic incentives (such as revenues from the exports) by optimising the domestic energy system (supply and demand of each energy form), the energy exchanges within the multiregional system area, and with the external markets, in an integrated manner.

Model was thought and designed as a comprehensive framework, able to simulate national and/or over-national constraints, in a long time horizon (until 2050) with the flexibility to also support analysis in a medium term (2030). All the potential export routes are represented like “processes” with specific techno-economic characteristics, and are identified through “exit points” determining the borders of the multiregional system under analysis (see Table 2). All the possible directions of exports are taken into consideration: “gas to Russia”, “gas to China”, “gas to the Mediterranean area (via Turkey)”, “oil to the Mediterranean area (via Turkey)”, “oil to China”, “oil to Russia”, “oil to Iran” and “gas to the Indian Subcontinent”.

The TIMES-CAC-4R model has been launched and solved with a MILP (mixed-integer-linear programming) method, based on which the more suitable size, among the available options, of each cross-Country infrastructure is selected (included in the optimal solution).

2.2. A composite risk parameter for energy export

Central Asian energy-exporting countries have recently started to search for “security of energy demand” and to design more comprehensive strategies for their future export plans. Together with the well-known “reduction of concentration”, alternative metrics have been identified in order to keep track (and estimate) the

³Model can run in two modes: with exogenously defined export levels per each direction of export [24], or with endogenously defined export levels through the most profitable route and destination.

Table 2. New possible pipelines: main characteristics in the TIMES-CAC-4R model.

Main characterisation parameters (*) (**) → :	Approx. length, <i>km</i>	Capacities (<i>M.bbl/day</i>)	Investment cost <i>M\$'2000/(PJ/a)</i>	Annual flows <i>PJ/a</i>	Var.O&M cost <i>M\$'2000/PJ</i>	
New oil pipelines, with the rest of the world						
KZK-MED, via AZJ (^) (&)	GEO, TUR	1500	0.24/0.72/1.2	18/22/26	480/1440/2400	1
New gas pipelines with the rest of the world						
			(<i>Bcm/a</i>)			
TKM-RF, through KZK	RF, UKR/BLR	2000	28.5/51.5/80	16/20/24	1000/1800/2800	4
TKM-CHI, through UZB/KZK	–	1500	24.5/30/35	16/20/24	850/1050/1250	3
TKM-CHI, through UZB/TJK/KYR	TAJ, KYR	1500	14/23/28.5	16/20/24	500/800/1000	3
TKM-MED sea, through AZJ	GEO, TUR	^1500	5.5/8.5/20	18/22/26	200/300/700	6

(*): Start year = 2015, Lifetime = 40 y, Fixed O&M = 5% of the investment cost, own consumption: 0.9% for gas pipelines, 0.5% for oil pipelines; (**) data from [25]; (+): CAC = Central Asia Caspian, AZJ = Azerbaijan, KZK = Kazakhstan, TKM = Turkmenistan, UZB = Uzbekistan; (++): BLR = Belarus, CHI = China, GEO = Georgia, KYR = Kyrgyzstan, RF = Russian Federation, TAJ = Tajikistan, TUR = Turkey, UKR = Ukraine; (^) under the Caspian sea; it refers to the offshore oil pipeline from Kazakhstan to Azerbaijan; (&) associated with the possible expansion of the Baku–Tbilisi–Ceyhan pipeline (BTC) 0.5 Mbb/d.

additional energy-related and non-energy-related characteristics of the potential importers, which may have an impact on the strategic decisions of the exporters.

Based on the identified markets of interest for the CAC area, and the identified potential routes of exports, a composite risk has been calculated by combining a geopolitical-socioeconomic risk with a market liquidity-related indicator, with an estimate of the potential of local resources, and with a factor representing the long-term environmental targets of the candidate importers. Table 3 summarizes the values used in the present analysis.

Historical and established economic relations with Russia (e.g. Kazakhstan is a Member State of the Eurasian Economic Union) have been also taken into consideration by assuming a medium-to-long term agreement on a minimum amount of oil supply through the existing Northern routes (through Russia). Such minimum amount of oil⁴ is, therefore, not subject to an optimal allocation decision, rather it aims to keep track of the actual bilateral relations and the persistent resistance to change over the time.

The present analysis includes only crude oil and natural gas in the quantification of the four energy-related components of the composite risk indicator. In this analysis, coal has not been considered a “key” energy commodity for the captive infrastructure investments and resource allocation problem of the CAC Area⁵.

2.3. Scenario analysis

The structure of the TIMES-CAC-4R model allows to fully include the concept of energy security in the analysis. The explicit representation of the pipelines (existing, and new options available in three different lump-sizes per each possible new route), the possibility to set national-specific and cumulative environmental targets at the same time, the opportunity to prioritize domestic energy use (inelastic demands), are all tools that can be used to include and control most of the characteristics of the energy security issue.

The mixed integer programming problem is formulated as follows⁶ (2)–(6):

$$\text{Min } [cX] \quad (2)$$

subject to:

$$DX > = d \quad (3)$$

$$MX < = m \quad (4)$$

⁴ At least 30% of the oil exported from Kazakhstan in 2030 is supposed to be delivered through the Northern routes.

⁵ For example, both EU and China (two of the key potential partners) are expected to reduce the share of coal in the energy mix in the medium-long term.

⁶ This formulation is a variant of the one prepared and used in the FP7 REACCESS Project [28].

Table 3. Composite risk indicators and prices for export routes from CAC region.

	Price (\$USD/GJ)	R_c	$e^{(1-\frac{1}{R_f})}$	$(1 - \frac{P}{R})$	$\frac{PES2010}{PES2040}$	Composite risk parameter
Source:	Authors' elaborations	Authors' elaborations, based on Worldwide Governance Indicators ⁴	Authors' elaborations, based on [26]	Authors' elaborations, based on [26] and [27]	Authors' elaborations, based on [20], [21] and [22]	Authors' elaborations
Type:	Importing-market specific [by period]	Route specific	Importing-market specific	Importing-market specific	Importing-market specific	Route specific
Route	[2015,2050]					
Gas AZJ-MED	[7.46, 12.46]	92.4	2.386	0.92	1.181	239.6
Gas KZK-RF-EU	[2.00, 12.46]	67.5	2.386	0.92	1.181	174.9
Gas TKM-AZJ-MED	[7.46, 12.46]	97.4	2.386	0.92	1.181	252.5
Gas TKM-India	[0.00, 12.46]	100	2.612	0.961	0.468	117.6
Gas TKM-IRA	[0.00, 12.46]	86.2	2.472	0.983	0.735	154
Gas TKM-KZK-RF-EU	[2.00, 12.46]	87.1	2.386	0.92	1.181	225.9
Gas TKM-UZB-KZK-CHI	[5.00, 12.46]	98.6	2.501	0.954	0.485	114
Gas TKM-UZB-TAJ-KYR-CHI	[5.00, 12.46]	99.6	2.501	0.954	0.485	115.2
Gas UZB-KZK-RF-EU	[2.00, 12.46]	87.1	2.386	0.92	1.181	225.9
Oil AZJ-MED	[10.96, 15.96]	92.4	2.386	0.92	1.181	239.6
Oil KZK-AZJ-MED	[10.96, 15.96]	97.4	2.386	0.92	1.181	252.5
Oil KZK-CHI	[7.68, 11.18]	60.4	2.501	0.954	0.485	69.8
Oil KZK-IRA-World	[0.00, 11.18]	86.2	2.472	0.983	0.735	154
Oil KZK-RF-MED	[6.00, 14.37]	67.5	2.386	0.92	1.181	174.9

⁴ www.govindicators.org.

$$R(r) * Q_t(r) \leq (1 - b) * \text{Max} \{R(r) * Q_{1,t}(r)\} \quad (5)$$

and

$$\text{Sum}_r \{p_t * Q_t(r)\}_t \geq (1 - a) \text{Sum}_r \{p_t * Q_{1,t}(r)\}_t \quad (6)$$

The objective function minimizes the total system cost represented by the cost vector c and the decision variables vector X (such as the amount of new capacity for power generators, the boiler stock for space heating, the energy imports/exports, etc.). D (3) and M (4) are the demand-constraint and the technical-constraint matrices which aim to represent the relevant characteristics of the energy system of the Central Asian Caspian area. They set minimum and maximum conditions to respect (such as the minimum number of square meters to heat in the winter season, or the maximum potential of wind energy in the system), thus defining the space of feasibility of the constrained problem.

To investigate the vulnerability⁷ problem, a multi-stage (1 + n) approach has been designed with the aim of testing different maximum tolerated risks (defined as the product between quantities and composite risk parameters) for the system (5), and of calculating “risk-costs”, “risk-quantities”, “risk-revenues” trade-off curves. Trade-off curves are built by running the model at least “1 + n” times. Such approach keeps a pure economic interpretation when the “1 + n” scenarios are run, as the objective function is always a cost-based expression of variables. The concept of “security of demand” is taken into consideration in the formulation of the problem used for this analysis, through the composite parameter $R(r)$ aiming to reflect the comprehensive and intrinsic risk of the route on the basis of energy- and non-energy-related criteria.

$R(r)$ is a route-specific composite risk parameter, $Q_t(r)$ is the specific decision variable representing the quantity exported via route “r” in period t , so that $R(r) * Q_1(r)$ is the route-specific risk as calculated at stage 1, p_t is the exogenous selling price of the commodity in period t , and b is a set of deviation parameters (“n” elements) which has been set equal to zero at stage 1.

The operator *Max* has been applied to the “flow of the corridors”: it enables to assign an upper limit of tolerated concentration period by period, and to simulate different diversification targets (5).

A second type of constraint (6) has also been considered with the aim to control a minimum level of revenues from the energy exports (sufficient to develop the energy sector and sustain the national economies) when the parameter “b” is assumed to be greater than zero. The default value for parameter “a” is 0.

⁷ Which is generally associated with the concept of concentration/diversification and measured with indexes like the Herfindahl-Hirschman or Shannon-Wiener.

The sequence of scenarios has been run as shown in Fig. 1. A reference case has provided the estimates of quantities and revenues of oil and gas exports, and risk values, period by period. Risk reduction targets have been tested subject to three main hypotheses on the minimum level of yearly revenues (controlled through adjustments of the parameter “a”): the same as in the reference case ($a = 0$); a maximum relaxation of 10% ($a = 0.1$); a maximum relaxation of 20% ($a = 0.2$). The underlying assumption was that a minimum level of 80% of the revenues estimated with the reference scenario is required to keep a growing rate of the economic indicators of the area.

For this analysis, 17 points (runs) have been used to assess the performance of the system subject to several ($n = 16$) risk reduction targets with three different controls of the minimum acceptable level or revenues from the energy export. The entire space of solution was explored by reducing the risk with a rate of 5% per run (through adjustments of the parameter “b”) until the problem was found “infeasible” ($n = 17$).

3. Results

3.1. A reference scenario

A reference projection of the total primary energy supply (by energy form), and of the total final consumption (by sector), are shown in the following charts. Values are driven by the assumptions that the four countries develop with an economic trend of around +4.5% (in terms of GDP, in average) and with a much lower population growth rate (+1.2%, in average) in the long-term. Without specific cooperative efficiency improvement strategies, and without specific emission reduction goals, the total supply is projected to be more than three times higher than in the base year, while the final consumption (the industry in particular) is projected to grow even faster (see Fig. 2). The resulting efficiency of supply

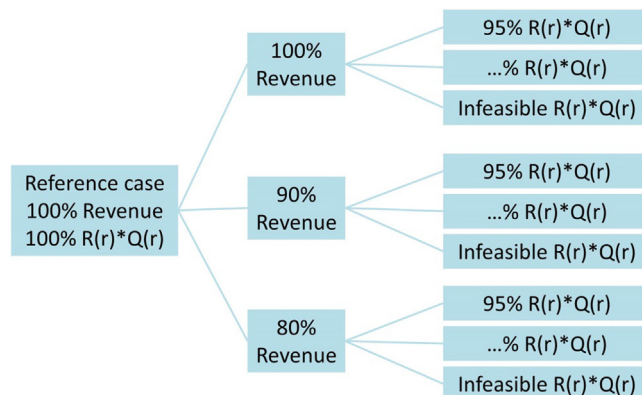


Fig. 1. Scenario tree (from the right to the left: reference scenario, revenue constrained scenarios, risk constrained scenarios).

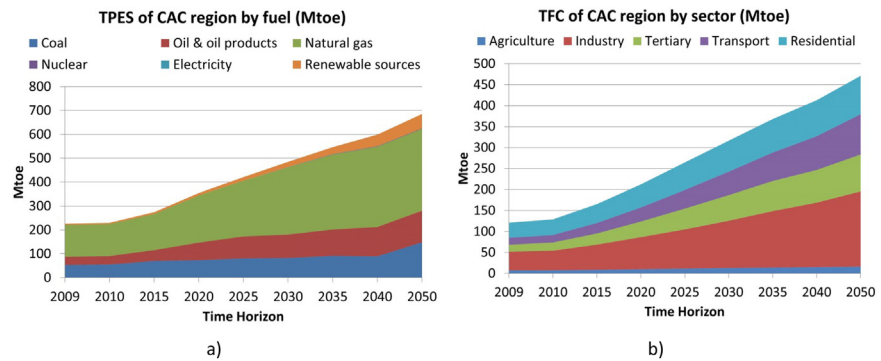


Fig. 2. Total Primary Energy Supply (TPES) and Total Final Consumption (TFC) of the CAC region in the reference case a) by type of fuel; b) by sector.

indicator (TFC/TPES) makes the decoupling between the amount of energy supplied and consumed evident, and points out the significant efficiency improvement of the secondary transformation processes in the medium-long term. But no policy or measure drives such choices; the inelastic internal energy service demands and the willingness to export (represented though the prices seen by the different importers) are the only “forces” determining the share of production for domestic consumption and the share remaining for exporting.

Alternative scenarios (for example environmental-oriented scenarios) may lead to different configurations of the integrated system. For example, the actual amount of natural gas available for the international market is strongly dependent on the future internal goals of the four countries in energy intensity reduction, emissions control, industrial development, and strategic approach. The multiregional system is assumed to be able to exploit the oil and gas reserves of the Caspian area in a cooperative way, as well as to build the required cross-border infrastructures, which would make the export levels of the entire area more convenient (cost-effective)⁸.

3.2. Risk against total system cost

The trade-off lines between “risk” against “total system cost” in three cases (for Revenue 100%, 90% and 80%) provide quantitative insights on the room for vulnerability-of-export reduction, and show the sensitivity of the risk indicator to revenue-control strategies. Results are shown in Fig. 3.

The graph can be divided into three major areas. The first one (top-left) shows that within a total cost increase of 5%, the system can sharply decrease the risk

⁸ For this study, a non-cooperative approach has been used in the area of emission reduction. Kazakhstan has been considered the only Country with a CO₂ restraint strategy in place, aiming at freezing the GHG emission per capita in the long term at the value of 2020.

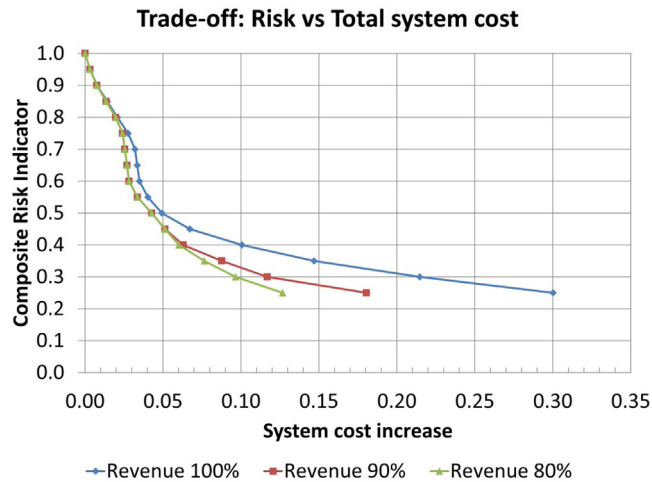


Fig. 3. Trade-off curves: Risk (y-axis) against Total system cost (x-axis).

indicator by 50% with respect to the reference case. The second area covers the risk decrease from 50% to around 20%, and shows a high sensitivity of the total system costs to such challenging goals. For example, a further risk reduction of 10% (from 50% to 40%) can be obtained with an additional extra cost of 5% (blue line). The third area, which is below 20% of risk reduction, results as “infeasible” for the Central Asian Caspian system, when it is subject to the minimum revenues control. Only a more significant relaxation (e.g. revenues 70%) of such a “vital” source of value would allow to open more space for a further risk reduction.

Chart can be also read in a comparative manner across the three revenues control options. A reduction of risk of 20% (from 1 to 0.8 in the vertical axis) does not result in any loss of revenue (lines overlap). For lower levels of risk (below 0.8), the wish of keeping the same amount of yearly revenues as in the reference case generates higher costs in the system, so that the blue line is always above the red one (and the latter is always above the green one).

By construction, the system can respond to the risk reduction targets in different ways: by changing the routes and lowering the associated risk, by adjusting the export volumes and capacities, by changing the domestic energy mix and allocating the most profitable and less risky commodity to the external market. While the first option is “cost-free”, the other two may require extra investments (for infrastructures and/or for different technologies in the system) to keep constant level of revenues from the export. An overview of the response of the system in terms of number of “activated” corridors, by scenario, is shown in Fig. 4.

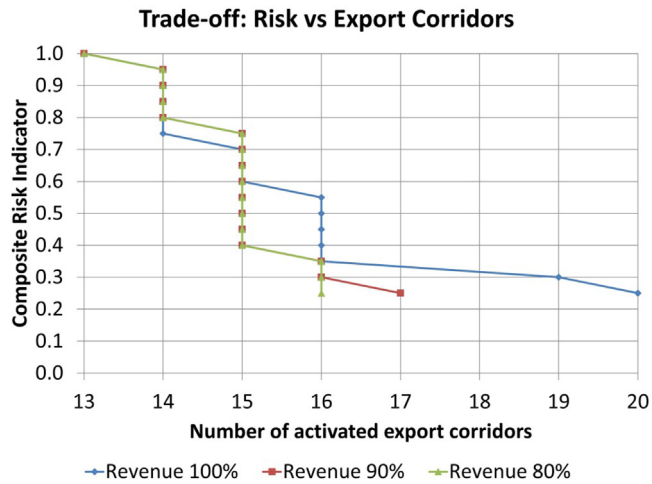


Fig. 4. Trade-off curves: Risk (y-axis) against Number of export corridors (x-axis).

A 5% decrease of the risk indicator requires constructing one more infrastructure to the Western direction (new oil pipeline from Azerbaijan to the European market). The stream of exported energy commodities in the various available corridors (utilization of the captive infrastructures) can be organised in such a way that the overall risk reduction is further decreased down to around 80%. Lower levels of risk need new/more corridors, up to twenty in case of very high risk reduction target and high revenues from the energy export. When the revenue control strategy is relaxed (to 90% or 80%), a lower number of corridors is required for reducing the risk of export of the Central Asian Caspian system. Moreover, the lump size of the activated infrastructures turns out smaller (e.g. for the undersea pipeline through the Caspian Sea), so that a lower system cost is generated.

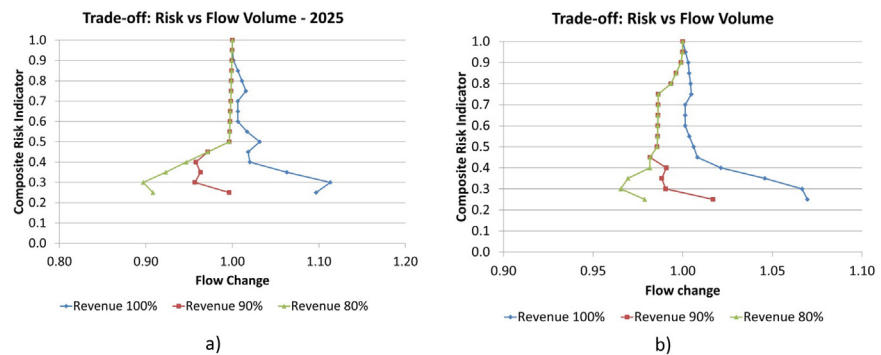


Fig. 5. Trade-off curves: Risk (x-axis) against Flow Volume (y-axis) in 2025 year; b) cumulative over the whole time horizon.

3.3. Risk against export flows

A complementary metric to measure the trade-off of the risk reduction is a comparison with the total volume exported (oil + gas) (see Fig. 5, a – for one key period (2025), and b – in terms of cumulative values over the entire horizon). Results suggest that in order to reduce the vulnerability, and at the same time ensure the level of revenues of the reference case, the CAC system is called to export more (from 1% to 7% more, as a function of the risk reduction target, in terms of cumulative export quantities), and to change the mix of destinations (routes).

Only with different assumptions about the minimum amount of revenues, the CAC system is able to lower the risk by reducing the volume exported. The two strategies of revenues control (90%, 80%) start diverging only after a risk reduction target of 45%. For less strict targets, the quantities exported in the two alternative cases are the same.

Table 4 provides more details about the response of the CAC system to the risk reduction targets for a critical turning point (50%). The composite parameter is very sensitive to the number and type of transit countries, so that the extension of the Caspian pipeline consortium (CPC) route is seen as a key factor in reducing the risk, while keeping the same amount of revenues of the reference case and the same

Table 4. Export flows by routes for three critical scenarios against the reference case.

Export flows by route (PJ) – Cumulative values					
No	Route	Risk – 100%	Risk – 50%		
-	-	Reference	Revenue 100%	Revenue 90%	Revenue 80%
1	Gas AZJ – MED	1489	1592	1477	1477
2	Gas KZK – RUS – EU	3255	3417	3255	3255
3	Gas TKM – AZJ – MED	0	0	0	0
4	Gas TKM – India	3480	3480	3480	3480
5	Gas TKM – IRA	2153	1854	2142	2142
6	Gas TKM – KZK – RF – EU	10914	11644	10916	10916
7	Gas TKM – UZB – KZK – CHI	12409	12876	12392	12392
8	Gas TKM – UZB – TAJ – KYR – CHI	0	0	0	0
9	Gas UZB – KZK – RF – EU	0	0	0	0
10	Oil AZJ – MED	13866	13917	13828	13828
11	Oil KZK – AZJ – MED	13435	9150	6150	6150
12	Oil KZK – CHI	2660	3196	3422	3422
13	Oil KZK – IRA – World	0	0	0	0
14	Oil KZK – RF – MED	15807	19167	21663	21663

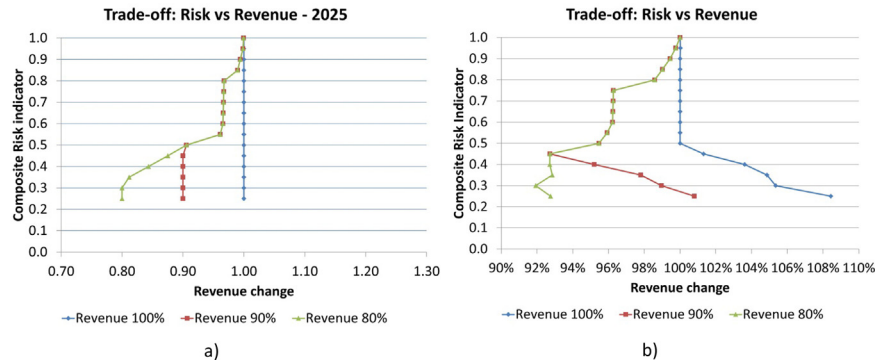


Fig. 6. Trade-off curves: Risk (x-axis) against Revenue (y-axis) a) in 2025 year; b) cumulative over the whole time horizon.

market destination (EU). A reduction of exported quantities (oil in particular) results cost-effective only in the case of revenues control relaxation (to extent of -10% and -20%): the two strategies behave in the same way at this point of the trade-off curves, and start to diverge only for more ambitious risk reduction targets.

3.4. Risk against revenues

The energy-producing Central Asian Caspian countries are highly dependent on energy exports, and this dependence typically results in large share of the energy sector to the GDP and fundamental contributions to annual State budgets. The trade-offs between the risk and the revenues from oil and gas export are shown in Fig. 6, for one key period (2025), and in terms of cumulative values over the entire horizon. Results make evident that the minimum control level is saturated for single specific periods (e.g. 2025), but not in terms of cumulative values. Exported quantities and revenues increase when the risk reduction is below the critical threshold of 50%. This is due to the higher amount of natural gas and oil exports to the East (China), which allow to exploit alternative routes with much lower composite risk values, as well as to increase the consequent overall revenues (quantities) from the export. On the other hand, such a configuration of the export flows generates a higher cost function (see paragraph 3.2) as it involves more investments in infrastructures.

4. Discussion and conclusions

When compared with the simulation based on the minimisation of a standard concentration indicator (e.g. Herfindahl-Hirschman Index), the reduction of the “composite risk” indicator for energy exports, as defined in paragraph 2, results in a different distribution of the export flows. Only when the risk reduction target is assumed to be “extreme”, and when the revenue constraint is relaxed (so that low revenues are acceptable), the two problems show similar outcomes. This is meant

to say that in the case of complex export problems, alternative/adjusted metrics (rather than the standard HHI) may depict different (probably “more consistent”) images of the actual levels of vulnerability of the exporting countries.

Four main components have been identified to estimate the composite risk: a geopolitical-socioeconomic one, a market liquidity-related, an energy-specific, and an environmental-oriented.

According to our analysis, there is a big room for reducing the risk of export that the CAC area is currently facing; the cost of such reduction would be relatively small (5% greater than the reference case) for a significant improvement of the indicator down to 50%.

However, if the Central Asian Caspian system is subject to additional environmental-oriented policies, different trade-offs and responses of the energy variables can be generated, particularly because of the greater sensitivity of the system to the natural gas allocation issue. Future scenarios are going to explore new hypotheses about future policies and measures, in order to make a more robust assessment of the vulnerability issue in the area.

Declarations

Author contribution statement

Aidyn Bakdolotov: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Rocco De Miglio: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Yerbol Akhmetbekov: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Kanat Baigarin: Analyzed and interpreted the data.

Funding statement

This research was funded under the target program No.0115PK03041 “Research and development in the fields of energy efficiency and energy saving, renewable energy sources and environmental protection for years 2014-2016” from the Ministry of Education and Science of the Republic of Kazakhstan.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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