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Coal mine methane in Kazakhstan: economic and environmental case study

Sergey Vassilyev, **Galym Iskakov**

Public Foundation “Environmental Fund for the Development of Almaty” Karasu m/dist., 22, Ozernaya str., Almaty, 050048, Kazakhstan

ABSTRACT

The study aimed to evaluate the economic and financial viability of a coal mine methane (CMM) utilization project in Central Kazakhstan, demonstrating a methodology for similar initiatives. The analysis was based on the 2013 project proposed by the US Environmen-tal Protection Agency (EPA) that intended to capture methane emissions from six coal mines for electricity generation, yet was never implemented. The study's relevance stems from Kazakhstan's 2030 methane pledge, recent progress in the country's climate change-related policy, mineworker mortality in 2023, and the shift of mines ownership. Building upon the technical specifications of the 2013 US EPA project, this research em-ployed standard financial and economic cost-benefit analysis (CBA). The financial model utilized a traditional discounted free cash flow approach, while the economic model in-corporated additional factors like the value of statistical life (VSL), shadow pricing, as well as benefits associated with mitigating ozone health impacts, crop damage, mine ex-plosion risks, and CO2 emissions. The economic model has indicated a positive net pre-sent value of $243 mln and 42% internal rate of return. The financial analysis also sug-gests potential profitability under fair electricity and carbon pricing market conditions. To assess project robustness under varying economic and financial assumptions, the study included a sensitivity analysis. The research has likewise leveraged prior CMM-related studies in Kazakhstan and provides valuable guidance for analyzing similar projects. In addition, it also highlights the need for certain adjustments in the current legislation to incentivize such projects, as well as to promote environmental sustainability and social development by mitigating methane emissions, which aligns with Kazakhstan's climate goals.

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CONTACT **Sergey Vassilyev** svassilyev@yahoo.com, Public Foundation “Environmental Fund for the Development of Almaty” Karasu m/dist., 22, Ozernaya str., Almaty, 050048, Kazakhstan

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1. Introduction

A series of methane explosions at Central Kazakhstan's coal mines between 2021 and 2023 claimed 57 lives. Such incidents highlight not only the human cost but also the safety risks associated with uncontrolled methane release during coal mining (Küçük & Ilgaz, 2015). Echoing similar events from 2004-2011 with 104 casualties as shown in Table I., these accidents prompted the Kazakh government to push for a change in the ownership of ArcelorMittal Temirtau JSC (AMT) that resulted in ArcelorMittal, an international steel group, selling its stake to a local investor in 2023, and the company's rebranding as Qarmet JSC (Qarmet) (GMK Center, 2023).

Table I. Explosions at AMT coal mines in 2004-2023.

Mine	Accident reason	Fatalities	Injured	Date
Lenina	Methane explosion	23	3	2004
Lenina	Methane explosion	41	12	2006
Abayskya	Methane explosion	30	-	2008
Tentekskaya	Coal and gas blast	5	-	2008
Tentekskaya	Coal and gas blast	3	1	2009
Kuzembayeva	Coal and gas blast	2	-	2010
Abai	Gas and coal blast	6	2	2021
Kazakhstanskaya	Fire	5	-	2023
Kostenko	Methane explosion	46	-	2023
TOTAL		161	18	

Local news sources in Kazakhstan (Tengrinews, 2023).

Beyond the immediate human cost, methane is also recognized as a potent greenhouse (GHG) gas with a global warming potential (GWP) of 28-36 and 84-87 times that of CO2 over 100 years and 20 years, respectively, a significant increase from earlier estimates (US EPA, 2023). The coal mining industry is one of the major contributors, accounting for roughly 11% of global methane emissions from human activities (Miller et al., 2013; Schwietzke et al., 2016).

Recognizing the urgency of reducing methane emissions, international efforts are underway. Discussions like these in Miller et al. (2021) deem methane a "super pollutant", as well as emphasize capturing methane from various sources and improving agricultural practices. Implementing such strategies, alongside a global methane agreement, could significantly reduce near-term warming. Following COP26, the Glasgow Climate Pact solidified the international commitment to this goal, aiming for 30% reduction in methane emissions by 2030; and was followed by the Global Methane Pledge (GMP) endorsed by over 120 countries collectively responsible for 50% of global human-caused methane emissions (UNEP & CCAC, 2022).

The Republic of Kazakhstan (RK), a country possessing vast energy resources, is well-positioned to contribute to these efforts, and has committed to 30% reduction in methane emissions by 2030 at COP28 (GMP, 2023). As the world's 9th largest country, Kazakhstan boasts substantial oil, natural gas, and coal reserves, making it a significant actor in the international energy market. However, its domestic electricity supply is poorly diversified, with aging power-generation assets heavily relying on fossil fuels (KEGOC, 2022). Local supply often struggles to meet demand, with peak periods requiring imports, primarily from Russia (Kursiv Media, 2023).

Recognizing the need to diversify energy sources and enhance environmental protection, Kazakhstan has set ambitious renewable energy (RE) goals – the country aims for 50% of its 2050 energy supply to come from renewables and nuclear, ultimately achieving carbon neutrality by 2060 (President of the RK, 2023). KEGOC, the national grid operator, has outlined these goals within the framework of the Energy Balance of Kazakhstan until 2035. This plan assumes expanding the installed generation capacity up to 44 GW by building new renewable and traditional generation systems LS (2023).

One promising diversification avenue lies in utilizing coalbed methane (CBM), a natural gas found in coal seams. Kazakhstan possesses abundant CBM reserves estimated at 2.0-4.3 tn m^3 (Wang et al., 2024). Yet, CBM remains largely untapped, presenting a unique opportunity.

This context highlights the timely opportunity to revisit and update the comprehensive pre-feasibility study sponsored by the US EPA in 2013 that focused on implementing a Coal Mine Methane (CMM) Drainage and Utilization system across six AMT-owned mines in Central Kazakhstan (US EPA, 2013). While it provides a valuable foundation, recent events necessitate updating data on mine conditions, methane emissions, and potential CBM reserves to ensure a robust cost-benefit analysis (CBA) of the proposed project.

It is noteworthy that this research targeted CBA and not updating the EPA study itself. Qarmet, the current owner of the coal mines, is best positioned to harvest and upgrade the information on CMM reserves and potentially implement technological advancements within their specific context. Against this background, this study aimed to demonstrate how valuation techniques can be applied to this real-world energy project via a comprehensive CBA.

Furthermore, Qarmet's current financial standing – characterized by acquisition costs ($286 mln), debt obligations ($450 mln in deferred payments) (GMK Center, 2023), as well as ambitious expansion plans targeting 64% increase in steel output and 47% boost in coal mining (Forbes Kazakhstan, 2024) – requires careful review. These factors, coupled with the recent tragic accidents, underscore the urgency of addressing methane emissions effectively.

By providing a comprehensive CBA with complete methodology, this paper aims to evaluate the economics of the EPA-proposed project and inform investment decisions, contributing to a cleaner and safer future for Kazakhstan's energy sector. It targets not only Qarmet and Kazakhstan's government, but also the academic community, contributing to the knowledge base on cost analysis of alternative energy sources in developing countries. The paper is structured as follows: Section 2 describes the methodology and key assumptions of the CBA model; Section 3 presents the model outputs, sensitivity analysis, and discussion; and, Section 4 contains conclusions.

2. Model description

2.1. Methodology

The primary goal of this study was to conduct an economic analysis of project feasibility from the perspectives of three key categories of project participants: (i) financial investors in the power plant (both equity and debt holders), (ii) coal mine owner, and (iii) society at large. To achieve this, the research team has developed a comprehensive economic model based on the standard discounted cash flow (DCF) approach.

This study comprised a thorough collection and review of data from public sources, including academic literature, business journals, news agencies, ArcelorMittal's official press releases, as well as state agencies and international organizations; and, expert opinions from the energy and financial sectors. Additionally, the authors conducted site visits to relevant projects, including a pilot coal methane power plant at the Lenina Mine operated by ArcelorMittal and a larger-scale coal methane power plant in Doncaster, United Kingdom. These visits took place several years ago when ArcelorMittal was still the owner of Qarmet, and included interviews focused primarily on the technical aspects of operations.

The economic model applied in this study was specifically designed to assess the net benefits accruing for each participant category:

1. Financial analysis for investors has estimated the private net benefits for financial stakeholders, focusing on revenues from electricity sales and carbon allowances. The model evaluated the power plant profitability from the point of view of equity and debt investors;

2. Financial analysis for mine owner has captured the private net benefits specific to the coal mine owner, including increased mine productivity, reduced compensation costs for accidents and injuries, decreased environmental fees, and revenues from gas sales;

3. Economic analysis for society has expanded the analysis to consider broader social benefits, incorporating both private gains and additional public advantages. The social benefits include GHG reductions, enhanced public health, improved agricultural production, and lower mine explosion risks. The benefits underwent quantification and monetization to render a comprehensive understanding of the project's impacts on social welfare.

Fig. 1. below visually summarizes the methodology, outlines the linkages between different models, and highlights the economic techniques applied at each stage of the analysis. The following sections describe key project assumptions, types of benefits (private and social), and specific economic techniques used.

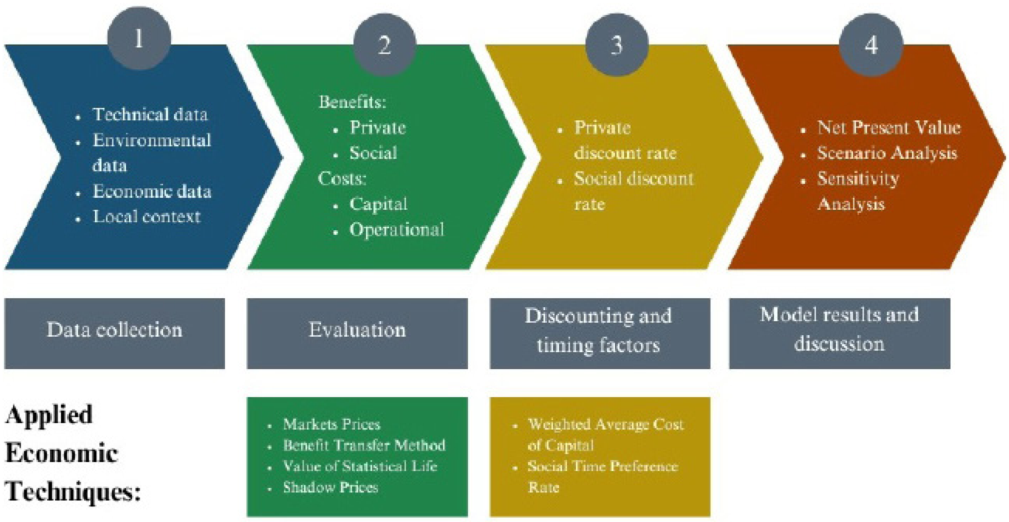

Figure 1. Methodology matrix

2.2. Theoretical framework and background (literature review)

The academic literature on cost-benefit analysis has evolved significantly over the past century, with early contributions focused only on public sector investments in infrastructure, health, and environmental protection (Johansson, 1993; Prest & Turvey, 1965). In high-income countries, CBA methodologies have been subject to progressive refinement to include a wider array of economic and social benefits. However, in middle-income and resource-rich countries, the application of CBA to energy projects, particularly renewable energy, was relatively limited until the early 2000s, largely due to unique economic and regulatory challenges (Ramadhan & Naseeb, 2011; Yang, 2009).

In the context of coal methane utilization, in the late 1990s and early 2000s the literature was also scarce focusing primarily on technical and regulatory aspects, with little emphasis on comprehensive economic evaluations (IEA, 2009; US EPA, 1998). Yet, recent years have witnessed a noticeable growth of studies examining the economic feasibility of CMM projects, particularly in large and resource-rich countries.

For example, (Hummel et al., 2018) explored methane drainage optimization in Indian coal mines. The study by (Nepsha et al., 2023) examined the economic benefits of CMM utilization in Russia, highlighting the potential for cost savings and emissions reductions. Similarly, Sander & Connell (2012) study on enhanced coal mine methane drainage in Australia underscored the importance of supportive policies, such as CO2 penalties and electricity pricing, for project viability. Wang et al. (2023) research on coalbed methane in China further confirmed the economic and environmental benefits of methane utilization, although it also noted the impact of policy uncertainties on project growth.

This study aims to contribute to this expanding body of literature by providing a detailed economic evaluation of a CMM project in Kazakhstan, a country with significant CMM emissions but limited previous thematic research. This research not only fills a gap in the existing literature but also offers a replicable framework that can be applied to similar projects in Central Asia and other developing regions. The methodology and findings presented herein are intended to inform future research and policy decisions, particularly in countries where energy market dynamics differ from these in high-income economies, ensuring the continued relevance and applicability of CBA in diverse economic settings.

2.3. Project description

Qarmet JSC owns and operates eight underground coal mines in Central Kazakhstan, six of which are classified as highly gassy with methane content ranging between 8.5 and 27.0 m^3 per ton (US EPA, 2013). To address safety concerns and improve methane capture capabilities, the implementation of methane drainage systems is necessary. As regional gas consumption and local prices are insufficient for direct coal mine methane (CMM) consumption by households and businesses, the

EPA study concluded that utilizing CMM for electricity and heat generation was the most viable option, and suggested the construction of several small power plants (2-3 units per mine) connected by a single gas pipeline. These power plants would utilize captured CMM as fuel to generate electricity, which then could be sold to the market or used in Qarmet's steel production.

The (US EPA, 2013) study estimated CMM levels to be sufficient for building an energy complex with the total installed capacity of 40 MW in two phases: the 19 MW phase followed by the 21 MW phase, with the second phase contingent on the success of the first, as shown in Table II. The total project investment was estimated at $54 mln, including $38.6 mln under Phase 1 and $15.4 mln under Phase 2. The combined capacity of the power plants was estimated at 298 mln kWh per annum, with the estimated project's operational life of 30 years, totaling 32 years due to the potential delay in completing Phase 2. The project was expected to achieve annual methane consumption exceeding 226 mln m^3.

Table II. Project installed capacity by phase and mine.

Mine	Phase 1 installed capacity (MW)	Phase 2 installed capacity (MW)	Total installed capacity (MW)
Kuzembayeva	3	4	7
Saranskaya	2	10	12
Abayskaya	8	3	11
Kazakhstanskaya	2	0	0
Lenina	3	3	6
Tentekskaya	1	1	2
Total	19	21	40

Based on the pre-feasibility study's assumptions, the project was expected to have a positive net present value (NPV) of $7.6 mln at 10% discount rate with the internal rate of return (IRR) of 13.3% for a 10-year equity-financed scenario. The sale of carbon credits, if included into the analysis, can significantly improve the project's financial viability, pushing the NPV up to $53.3 mln and IRR up to 30.9%, as well as shortening the payback period from six to four years. Consequently, the EPA recommended conducting a full feasibility study, incorporating an in-depth analysis of Kazakhstan's current climate change regulations. It is important to note that the financial results described above come from the US EPA's pre-feasibility study of 2013 and may not reflect current market conditions. The original study referred to ArcelorMittal Temirtau JSC as the owner of the mines, updated to Qarmet JSC in this paper to reflect the current owner.

2.4. Model assumptions

The EPA pre-feasibility study contained important and detailed information on the capital cost structure and technical feasibility of executing the project. However, the model required further improvements, especially in terms of accuracy of the project's valuing costs and benefits, and clarification of funding sources (debt to equity structure). As the EPA study was published in April 2013, it didn't capture the annual devaluation of Tenge (Kazakhstan currency) during 2014-2022. The EPA's main financial analysis scenario also suggested that electricity prices would rise faster (11.4% annually) than operating and maintenance (O&M) costs (7.4%), which may not be necessarily true as evidenced by the historical data from the Consumer Price Index (CPI) and electricity tariffs statistics (can be explored in more detail in the Supplementary Data file attached to the study). Hence, the CBA presented in this paper manifests an advanced version of the EPA's financial model with additional economic analysis and certain other factors detailed as shown in Table III.

Table III. Model assumptions

Parameter	Value	Source/Comment
Annual electricity output	298 mln kWh	(365 days x 24 hours x 40 MW) / 1,000 based on 75% of Engine Capacity Factor
Electricity price	¢3.00 per kWh	Mean electricity tariffs obtained by the Single Purchaser in 2H2023 converted to USD at official rates set by the National Bank (RFC for RES, 2024)
O&M costs	¢1.82 per kWh	EPA's assumption based on data obtained from potential suppliers and adjusted to January 2024 prices using US Bureau of Labor Statistics' CPI Inflation calculator (US BLS, 2024)
Average number of employees	35	5 employees per site x 6 sites + 5 admin stuff
Mean gross salary per employee	$830 per month	Mean salary in the region, according to Kazakhstan's statistical agency (QazStat, 2023)
Annual methane consumption	226 mln m^3	EPA estimates based on data obtained from AMT
Funding structure	40% - equity 60% - debt	Observed data in Kazakhstan

Cont. Table III.

Debt financing terms	7 years for each of the two installments at 7.3% annual interest rate	Observed data in Kazakhstan, National Bank of the RK
Annual CO2 mitigation	1.8 mln tons	EPA estimates with some adjustments to utilization rate (85% versus 100% assumed by EPA)
Total capital costs	$72 mln	EPA assessment adjusted to January 2024 prices using US Bureau of Labor Statistics' CPI Inflation calculator (US BLS, 2024)

2.5. Valuation of private benefits

As the project was suggested for implementation by separate entities, two project participants receive private benefits: the mine owner (Qarmet, in particular) and financial investors, including equity and debt investors. Private benefits have a monetary form and will be received in cash by each of the participants.

While the calculation of private benefits for project investors (presented in the Supplementary Data file attached hereto) is a standard procedure based on the formula below, the benefits for the coal mine owner require an additional review, detailed in further sections.

To calculate the project's net benefits, a standard discounted cash flow (DCF) model was used with the standard financial NPV applied (Damodaran, 1994):

$$NPV_{INV} = \sum_{i=1}^{n} \frac{FCF_i}{(1+r)^i} \qquad (1)$$

$$FCF = EBIT * (1 - CIT) - Capex + D\&A + \Delta WC \qquad (2)$$

, where

FCF is free cash flow,

EBIT is earnings before interest and tax (calculated separately for each type of project participant and explained in this section below),

CIT is corporate income tax (20% in Kazakhstan (Zan.kz, 2024)),

Capex is capital expenditure,

D&A is depreciation and amortization,

ΔWC is changes in working capital,

r is discount rate,

and n is number of periods.

Increased mine productivity. Project implementation will help boosting and stabilizing gas utilization, boosting the productivity of labor and operations by avoiding mine shut downs usually due to high methane content in ventilation systems. In its turn, higher productivity will lead to higher coal production and/or higher profit margins (IEA, 2009).

The data from previous years suggests that coal mining can reach up to 8.3 mln tons annually (ArcelorMittal, 2022, 2023a). The new owner (Qarmet JSC) aims to achieve an even higher target of 9.0 mln tons (Forbes Kazakhstan, 2024). Considering the average net margin of 17.5% within Kazakhstan's coal sector (KASE, 2024), a conservative estimate of 0.1% improvement in profitability due to the project's efficiency gains can yield significant financial benefits for Qarmet. It is important to acknowledge that while the project is expected to significantly reduce mine shutdowns, it may not eliminate them entirely. Therefore, the conservative assumption of 0.1% profitability improvement serves a cautious estimate to ensure a realistic assessment of the project's financial impact.

As Qarmet produces steel, there is potential to shift towards "green steel" production by involving processes that significantly reduce GHG emissions based on renewable energy and other advanced technologies like hydrogen or carbon capture (Muslemani et al., 2021). Yet, this model does not account for additional benefits related to the steel's reduced carbon footprint, as it assumes that the electricity generated will be sold to the Single Purchaser and not used directly in steel production. Additionally, coal pricing was not factored into the model as Qarmet owns both the steel production facilities and the coal mines. If the coal was owned by a different entity, the potential to sell less carbon-intensive coal at a higher price could be explored, and the pricing dynamics might differ, requiring separate examination.

Reduction of compensations for fatalities and injuries. The reduced risk of explosions diminishes expected compensations paid by Qarmet for fatalities and/or injuries as the result of mine explosions. The Kostenko Mine disaster in October 2023 serves a stark example of the financial repercussions of such accidents.

ArcelorMittal, the former owner, incurred significant costs (ArcelorMittal, 2023b), in-cluding a one-off payment equivalent to 10 years' salary (up to $180,000 in total, assuming the reported average coal worker salary at $1,500/month Anon (2023), covering all fu-neral and memorial expenses (around $5,270 per person as reported by Ranking.kz (2022), purchasing housing, repaying personal loans (deceased and family members) and covering education fees for children up to the age of 23 – bringing the total potential compensation per deceased worker to at least $300,000.

By mitigating the risk of explosions, the project has the potential to significantly reduce the aforementioned costs. The economic benefit from reduced expected compensation (BC), therefore, can be expressed mathematically as:

$$BC = E(C_1) - E(C) \quad (3)$$

, where

BC is benefit from reduced expected compensation,

$E(C_1)$ is expected compensation costs after project implementation and safety improvements,

and $E(C)$ is expected compensation costs before project implementation.

In simpler terms, implementing the project will allow Qarmet to potentially reserve less cash for anticipated compensation pay-outs in the event of mine accidents.

Reduction of environmental payments. According to the Tax Code of the RK, local emitters pay a tax of ¢8.0 for each ton of me-thane emitted Code of the Republic of Kazakhstan (2024). The project is expected to prevent the emission of 192 mln m^3 of methane annually. Using the EPA's Coalbed Methane Outreach Program data (US EPA, 2024), where 1.0 m^3 of methane weighs 0.6802 kg, this reduction equates to approximately 131,000 tons of methane emissions. At the rate of ¢8.0 per ton, the project implementation is expected to save Qarmet approximately $10,448 annually on these taxes (factored in the model).

Total net benefits for Qarmet. The net benefits for Qarmet JSC, therefore, represent a sum of all benefits excluding investment required inside the mines:

$$NPV_{QARMET} = \sum_{i=1}^{n} \frac{GS_i + BPI_i + BC_i + SE_i - I_i}{(1+r)^i} \quad (4)$$

, where

GS is gas sales (revenues from methane sold (set at "0" in this study),

BPI is benefits from improved coal mining productivity,

BC is benefits from reduced compensations for deaths and injuries,

SE is savings on ecological payments,

I is investment in coal mines,

r is discount rate applied by coal miner,

and n is number of i periods.

The detailed calculation of net benefits for the mine owner is presented in the Supplementary Data file attached to the study.

2.6. Valuation of social benefits

Social or public benefits can be defined as an increase in social welfare. As discussed in the next sections in more detail, methane emissions contribute to global warming, ground-level formation of ozone - a harmful air pollutant responsible for an estimated 500,000 premature deaths annually and damaging ecosystems and crops (UNEP & CCAC, 2021), and safety hazards within coal mining operations. In case of execution, the project may offer the following potential social benefits:

1) lower carbon dioxide (CO_2) and methane (CH_4) emissions;

2) due to capturing methane, significantly reduced risk of explosions and associated fatalities at coal mines;

3) mitigating methane emissions can contribute to lower ozone levels, potentially reducing respiratory illnesses and improving crop yields.

Valuating social benefits, particularly these related to environmental improvements, poses a challenge due to the absence of established market prices. Traditionally, economists address this through revealed preference (RP) analyzing individuals' actual behavior in the marketplace to infer their preferences for non-marketed goods, and stated preference (SP) methods, which rely on surveys or experiments to directly ask individuals about their willingness to pay (WTP) or accept (WTA) compensation for changes in environmental quality. These methods, along with the development of economic theory, have led to the emergence of various valuation techniques. Further details on RP, SP, and specific valuation techniques can be found in the relevant textbooks (Baker & Ruting, 2014; Haab & McConnell, 2002).

As the literature database has continued to include more studies on appraisal of different types of non-market goods, the Benefit Transfer Method has evolved (Johnston et al., 2015). In general, it suggests that an analyst may “borrow” a value of non-market good received in an original study and use this value to appraise benefits in the project or policy under analysis. This paper also employs this method, and when readily available market prices exist for goods or services directly linked to the specific benefits, they can be directly used in the valuation process as well. The following sections delve deeper into the chosen valuation methods for each social benefit.

Valuating benefits from GHG emissions reduction. Mitigating GHG emissions offers social benefits by improving air quality and reducing potential environmental damage. The project is estimated to annually prevent emission of 1.8 mln tons of CO_2.

Economists utilize various methods to estimate the value of carbon reductions, particularly the Social Cost of Carbon (SCC), which estimates “the total damage from now into the indefinite future of emitting an extra unit of GHG’s now” (Stern, 2007); and the Marginal Abatement Cost (MAC), which focuses on the most cost-effective ways to achieve a specific emission reduction target. Kontovas & Psaraftis (2010) provided a sufficient overview of the main methods to price carbon emissions. There is also a significant number of papers calculating WTP for GHG reductions, available in databases like EVRI and GEVAD .

While SCC and MAC do offer valuable insights, inherent limitations exist. Market prices directly reflect supply and demand, making them suitable for this analysis. The established carbon trading schemes likewise provide valuable benchmarks, e.g. $38.73/ton in California (CARB, 2023), and EUR 63.9/ton in the EU (EC, 2024). Yet, directly applying data from mature markets is inappropriate due to differing economic realities. Kazakhstan also has a carbon allowance market, still nascent due to limited trading activity (no official data was recorded in 2023 with the latest transaction registered in September 2022 at the carbon allowance price of 397 Tenge/ton (less than $1) Recycle.kz (2022). The conversations with local experts, including representatives of the International Green Technologies and Investment Projects Center and Ecojer Association , revealed offers around $3.2/ton during 2023, although lacking official verification.

Thus, considering the limited data and evolving market, a provisional value of $3.2 per ton was adopted based on industry insights. The limitations of this valuation highlight the need for further research. As Kazakhstan's carbon market matures and official data become available, economists can refine the analysis to incorporate more accurate market-driven values.

Benefits from mine risk reduction. Between 2004 and 2023, several severe mine accidents resulted in fatalities and injuries. As the CMM utilization leads to a significant reduction of accident risks and improved coal mine safety (Karacan et al., 2011; Mahdevari, 2019; Wang et al., 2023), the execution of the target project is expected to notably slash the number of such emergencies.

While valuating benefits from mortality risk reduction, economists use the Value of Statistical Life (VSL) concept. VSL can be defined as a WTP for a “1” in N risk reduction aggregated over N individuals (Robinson et al., 2018). Traditionally, there are two main approaches to calculating VSL. Whereas the first approach is based on contingent valuation when individuals are directly asked about their WTP for mortality risk reduction, the second suggests designing the *compensating differential model* based on labor market statistics.

According to Polat (2014), most of the existing VSL literature is based on the US data, and only a few studies were completed for developing markets, including Giergiczny (2008) study for Poland and Parada-Contzen et al. (2013) study for Chile. Giergiczny (2008) clarifies that during the last 20 years, only a few wage-risk studies were carried out in Europe, with most of them in the UK.

Polat (2014) provides at least two reasons, explaining why VSL valuation in middle-income countries differs from this in high-income countries. The first is that labor markets in the former are more segmented, with informal jobs having a higher proportion in the market structure. This implies lower expenditures for safety technologies and less control over safety issues. The second reason is that companies in middle-income countries show wider heterogeneity in size and finance (limited capital), which mainly means that the proportion of small and medium business dominates in the overall economy structure. Smaller enterprises with limited capital have lower access to safety technologies and are less prepared to adopt them.

Hence, for the purpose of valuating the VSL for the target project, the model uses Giergiczny (2008) study for Poland considering the similarities in economic transitions between this country and Kazakhstan. The Giergiczny (2008) model has the following semi-logarithmic functional form:

$$Ln(W_i) = \alpha_1 + \alpha_2 FAT_i + \alpha_3 FAT_i^2 + \beta X_i + \varepsilon_i \qquad (5)$$

, where

W is wage,

FAT is the fatal injury,

FAT2 is the fatal injury risk squared,

and X is a vector of 15 variables controlling the worker and job-specific attributes.

(Giergiczny, 2008) ran four separate regressions with varying breakdown levels by industry: one-digit, two-digit and three-digit levels according to the European classification of economic activity (NACE) (EC, 2022). As the result, VSL can be found through:

$$VSL = (\hat{\alpha}_2 + 2 * \bar{r} * \hat{\alpha}_3) * \bar{w} * 2000 * 10000 \qquad (6)$$

, where

$\bar{\alpha}_2$ is the risk coefficient,

$\bar{\alpha}_3$ is the coefficient for risk squared variable,

$\bar{r}$ is the mean risk in the sample (number of fatal injuries per 10,000 workers),

and w is the mean hourly wage.

Number of working hours is 2000.

Transfer of function was applied to value VSL for the target project. Hourly wage data for Qarmet's mine workers was crucial for this analysis and was obtained from the publicly available collective labor agreement for 2022-2024 containing wage information for AMT coal mine workers (Metallurgical Trade Union Zhaktau, 2023). The data was then adjusted to reflect 2022 and 2023 inflation rates using the official CPI, i.e. 20.3% for 2022 and 9.8% for 2023 (QazStat, 2024b). The hourly rate also included monthly and annual bonuses (both are guaranteed by the collective labor agreement), as well as pension contribution of 10%. That resulted in the estimated average hourly wage of a worker in Qarmet's coal division at $5.2 per hour. This level was applied to the (Giergiczny, 2008) model with 1.64 fatal injuries per 10,000 workers. The outcomes of the exercise are presented in Table IV below.

Table IV. VSL for Qarmet

	Model 1 No ind. dummy variables	Model 2 Ind. dummy variables at one-digit NACE level	Model 3 Ind. dummy variables at two-digit NACE level	Model 4 Ind. dummy variables at three-digit NACE level
Fatal at five-digit level				
Coefficient by fatality	0.01960	0.00717	0.00411	-0.00134
Coefficient by fatality_sq.	-0.001750	-0.000926	-0.000735	-0.000379
Linear combination of coefficients by fatality and fatality_sq.	0.014	0.0041	0.0017	-0.0025
VSL ($)	**1,453,247**	**433,323**	**178,164**	**-270,845**
Fatal at three-digit level				
Coefficient by fatality	0.0808	0.0572	0.0355	0.0273
Coefficient by fatality_sq.	-0.0107	-0.00769	-0.00461	-0.0038
Linear combination of coefficients by fatality and fatal_sq	0.046	0.032	0.02	0.015
VSL ($)	**4,792,150**	**3,352,827**	**2,136,797**	**1,555,582**

Giergiczny (2008) concludes that the estimates that are based on three-digit occupational risk provide a more reliable VSL estimation. The negative result in Model 4 at five-digit level is probably due to flaws in risk measure data. Hence, the VSL for the Qarmet project is expected to range between $1.6 mln and $4.8 mln, i.e. two times higher compared to Giergiczny (2008) estimate for Polish VSL in 2002. This seems to be logical as the mean wage at that time was about $2.6 per hour versus $5.2 applied in this study's model. As Polat (2014) found an even smaller VSL for Turkey (ranging between $14,000 and $1,473,000), a lower VSL boundary for the Qarmet project ($1.6 mln) was applied in the model.

Valuating public health and agricultural benefits of reduced methane emissions. Methane plays a crucial role in the formation of ground-level ozone as it reacts with other chemicals in the atmosphere (e.g. nitrogen oxides and volatile organic compounds) in the presence of sunlight. The oxidation process creates various compounds, including these stimulating ozone formation, where methane acts as a key precursor for the creation of tropospheric ozone, also known as ground-level ozone – one of the major air pollutants. Unlike the beneficial ozone layer in the stratosphere shielding us from UV radiation, ground-level ozone harms human health, causing respiratory issues, cardiovascular problems, and premature deaths; as well as damages crops, reduces yields, and contributes to smog formation (Abernethy et al., 2021; Dentener et al., 2005; EDF, 2023; Sampedro et al., 2023). This means that by mitigating methane emissions the target project may offer significant public health and agricultural productivity benefits.

To quantify them, the study has leveraged the estimates from the "Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions" published by UNEP in 2021 (UNEP & CCAC, 2021). This UNEP assessment provides monetary values (presented in 2018-level $/ton) for various methane emission effects across the countries, including Kazakhstan. The bullet points below summarize how these values were adjusted to reflect the 2023 economic conditions:

- Inflation Adjustments: The Consumer Price Index (CPI) inflation calculator from the US Bureau of Labor Statistics was used to account for general inflation between 2018 and 2023 (US BLS, 2024);

- Crop-Specific Adjustments: For the agricultural sector, adjustments were derived from the US Department of Agriculture (USDA, 2024) data to account for specific price changes in wheat, soybeans, maize, and rice.

Table V. below breaks down the estimated benefits per ton of methane emissions after inflation and crop-specific adjustments.

Table V. Value of economic benefits

Impact	$/t (2018)	$/t (2023)	Adjustment factor	
Value of reduced risks of ozone-related deaths in Kazakhstan	8.1	9.9	1.22	CPI calculator
Cost of asthma-related accident and emergency department visits due to ozone exposure in the closest peer country (Russia)	0.01	0.02	1.54	CPI calculator

Table V. Cont.

Negative impact on crop production	38.3	65.4	1.71	USDA data
Wheat	11.7	21.9	1.87	USDA data
Soybeans	6.6	10.0	1.52	USDA data
Maize	6.8	13.2	1.95	USDA data
Rice	13.2	20.3	1.53	USDA data
Forest	20.0	24.5	1.23	CPI calculator
Total	66.4	99.9	1.50	

Mitigating methane emissions offers a substantial economic benefit of $99.9 per ton, reflecting improvements in public health and agricultural productivity. The largest contributor to the economic benefits is the reduced negative impact on crop production, valuated at $65.4/ton. Public health enhancements also play a significant role, with a combined value of $9.9/ton for reduced risks of ozone-related deaths and asthma-related emergencies.

2.7. Shadow prices

Unlike financial analysis, which relies solely on observed market prices, economic analysis adopts a wider perspective by considering the “social value” of project inputs and outputs, encompassing social welfare on the national or regional levels. This necessitates adjusting these values to reflect their true impact on society. While the sections above shed light on the assessment of non-market benefits produced by the project, this section focuses on costs, specifically utilizing the concept of “shadow prices”. Shadow prices recognize that market prices often diverge from their true social value due to various factors like (Drèze & Stern, 1988):

- Market imperfections: Monopolies and oligopolies distort market mechanisms, causing price deviations from optimal levels;

- Government intervention: Price controls or subsidies imposed by the government can artificially alter market prices.

In such situations, prices from the financial analysis that uses available market prices should be adjusted by conversion rates when transferred to the economic analysis.

The EU Commission Guide EC (2014) proposes that conversion rates should be reported by national planning agencies. Yet, when conversion rates are not available from the government, the Guide recommends applying the Standard Conversion Factor (SCF) for most cash flows.

Among all the project parameters, only electricity prices were obtained from an imperfect market, which is heavily regulated by Kazakhstan’s government, mainly through the so-called mechanism of "marginal tariffs" set for most conventional energy producers and limiting their ability to increase prices. Hence, to calculate the Standard Conversion Factor for electricity prices the following formula was used:

$$SCF = RES \;/\; P = 4.31 \;/\; 3.00 = 1.44 \tag{7}$$

, where

RES is the weighted average tariff from 2023 renewable energy auctions as calculated in in the Supplementary Data file attached to the study (Qazaq Green, 2023),

and P is electricity price used in the private benefits calculation section.

Renewable energy auctions are a market-based mechanism that Kazakhstan's government uses to determine electricity prices for various types of RE sources. As this is a market-based mechanism, the authors believe it fairly reflects the markets realities and social value of electricity from the newly built sources.

2.7. Discounting and timing factors

Cost-benefit analysis necessitates discounting future benefits and expenditure due to the time value of money (Boardman, Greenberg, Vining, 2018). The standard weighted average cost of capital (WACC) was used to discount private benefits and costs in the model. The calculation and explanation of WACC are presented in the Supplementary Data file attached hereto.

For social benefits and costs, the social discount rate (SDR) should be used reflecting societal preferences for present versus future consumption (Pearce et al., 2003). One ap-proach to determining the SDR is the social opportunity cost rate (SOCR), which argues that public projects should be financed at a rate no lower than the returns from private invest-ments. Under this concept, if the government has an alternative private-sector project with a specific return, the discount rate for public projects should match or exceed that return (Lind, 1990). This study, however, adopts the alternative concept of the social time preference rate (STPR), calculated using the formula proposed by Ramsey (1928):

$$STPR=p+eg \tag{8}$$

, where

p is the utility discount rate. According to QazStat (2024a), in 2009-2022 Kazakhstan's mean death ratio totaled 0.8%, which was applied to the model (refer to Fig. 1.);

e is elasticity of marginal utility of consumption. Calculating e requires substantial data unavailable for Kazakhstan in this project. Thus, following the common practice for developing economies (Kula, 2004), the value of 1.64 was adopted from a relevant study in India;

g is an assumed long-term average growth of real consumption per capita. Kazakhstan's real GDP growth averaged 5.12% between 1996-2022 (World Bank, 2022).

As the result, 9.2% was used as the discount rate for the project's economic net benefits.

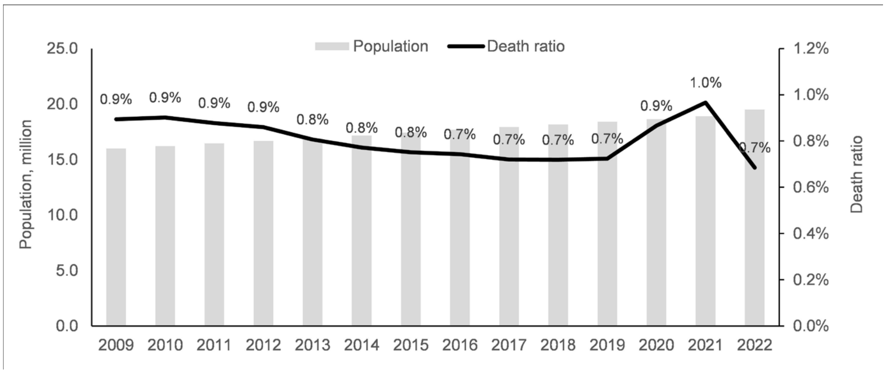

Figure 2. Death ratio in Kazakhstan in 2009-2022.

According to the EPA study, the project was planned for execution in phases over 32 years, with each phase lasting 30 years, and the 2nd phase starting 2 years after project initiation. Due to the difficulty of predicting future electricity prices and operation & maintenance costs, the key project parameters (Table II) are assumed to remain constant throughout the operational life. All prices within the model are expressed in constant 2023 US dollars, implying no inflation is considered, which means that the model is real, i.e. not nominal.

3. Model results and discussion

The proposed project offers significant economic and environmental benefits, including utilization of 226 mln m^3 of methane, resulting in a reduction of 1.8 mln tons of CO2 equivalent emissions, and generating 350 mln kWh of electricity annually. Economically, the project offers potential savings of $15.4 mln annually due to reduced health (ozone exposure) costs and improved crop yields. It is likewise estimated to create 35 new jobs and significantly decrease mine explosion risks, leading to potentially fewer worker fatalities and higher mine productivity. These factors contribute to a positive social value reflected in the calculated NPV of $243 mln and IRR of 42% under the economic model (detailed calculations are presented in the Supplementary Data file attached hereto).

Table VI summarizes the outputs of the financial and economic models.

Table VI. Model outputs at different levels of methane price

Parameter	Economic model outputs (public benefits)	Financial model outputs (private benefits)		
		Financial investor model	Mine owner model	Consolidated model
Discount rate	STPR = 9.2%	WACC = 9.5%	WACC = 9.5%	WACC = 9.5%
Sale of carbon allowances is not included				
NPV ($ mln)	Not applicable	- 46.2	15.6	- 27.7
IRR	Not applicable	0.5%	Not applicable	4.5%
B/C or PI	Not applicable	PI = 0.3	Not applicable	PI = 0.6
Sale of carbon allowances is included				
NPV ($ mln)	243	- 0.2	15.6	15.6
IRR	42%	9.5%	Not applicable	12.0%
B/C or PI	B/C = 4.1	PI = 1.0	Not applicable	PI = 1.2

* Due to the assumption that the owner of mines bears no project implementation costs, it is not possible to calculate IRR and PI.

Whereas the financial investor model exhibits negative NPV (minus $46.2 mln) and low IRR (0.5%), suggesting the target project might not be financially attractive for investors, the mine owner model shows positive NPV ($15.6 mln), assuming no incremental implementation costs. However, the overall NPV remains negative (minus $27.7 mln) with the project's IRR of 4.5%.

The inclusion of carbon allowance sales ($3.26/ton of CO2) significantly improves the financial attractiveness – up to $15.6 mln of consolidated NPV and 12.0% IRR. Yet, as the NPV remains negative for financial investors (minus $0.2 mln), it clearly shows that the project cannot be successfully implemented without the mine owner's participation.

Compared to the 2013 EPA study, the current financial model paints a significantly less optimistic picture for the project's financial viability. While the 2013 study projected a positive NPV ($7.6 mln) and high IRR (13.3%), the new model shows an overall negative NPV (minus $27.7 mln) and low IRR (4.5%), both models excluding carbon allowances. Under the carbon allowance case, the project remains unattractive for private investors with a negative NPV ($0.2 mln). This highlights a stronger dependency on the mine owner's participation, with this model showing a positive NPV ($15.6 mln). Therefore, the current model suggests the project's success relies heavily on securing carbon pricing mechanisms and full financial engagement of the coal mine owner.

The detailed calculation of financial benefits is presented in the Supplementary Data file attached to the study.

3.1. Sensitivity analysis

A sensitivity analysis was conducted on the economic model to assess its robustness under varying assumptions. Two key parameters underwent evaluation: carbon price and ozone-related cost avoidance. As discussed earlier, the initial estimate for carbon allowances was $3.25 per ton, which was based on discussions with local experts in Kazakhstan. Due to the nascent state of global carbon markets and the lack of documented evidence for a specific price in Kazakhstan, the sensitivity analysis explored the range of $0 to $10 per ton to account for potential future market fluctuations.

Similarly, the initial estimate for benefits from reduced ozone exposure was $100 per ton of methane avoided, resulting in $15.4 mln annual benefits. Given the potential for uncertainty surrounding the valuation of public health and crop productivity benefits in Kazakhstan's context, the analysis examined the range of $0 to $100 per ton to assess the impact on the project's viability.

As shown in Table VII., the project's economic net present value (NPV) remains positive even in extreme scenarios where both parameters are zero. This indicates that the project's economic viability is primarily driven by the benefits from reduced worker fatalities and fair market electricity pricing (as explained above in the Shadow Prices section, in the economic model tariffs were adjusted to the market prices obtained from 2023 renewable energy auctions) independent of carbon credit markets or the full extent of public health improvements from reduced ozone exposure.

Table VII. Sensitivity analysis of the economic model (NPV in $ mln)

		Price of carbon credit, $/t					
		0.0	2.0	**3.3**	4.1	7.0	10.0
Ozone-related cost avoided, $/t	0	48	81	**101**	115	163	212
	50	119	152	**172**	186	234	283
	75	154	187	**208**	221	269	319
	80	161	194	**215**	228	276	326
	90	176	208	**229**	243	291	340
	100	**190**	**223**	**243**	**257**	**305**	**354**

Furthermore, evaluating the model with the zero VSL (assuming no improvement in coal operations and explosion risks), the economic NPV drops to "0" with the IRR of 9.2%. This suggests that even without mortality reduction benefits, the project remains economically neutral from the societal perspective, indicating that the public is unlikely to oppose its execution.

The sensitivity analysis was also performed for the financial model, focusing on capital expenditure (capex) and electricity prices. The initial EPA assessment estimated capex at $54 mln (in 2013 prices) adjusted to $72 mln in this study's model to reflect 2023 pricing levels (as presented in Table 3. above). The sensitivity analysis considered potential underestimation of equipment price growth by examining a range of capex values, as construction costs can fluctuate over time. Additionally, electricity price, a significant economic driver, was tested between $3.00 and $4.50 per kWh, reflecting the latest (at the time of this paper), renewable energy auction results in Kazakhstan (Qazaq Green, 2023). Table VIII summarizes the financial model sensitivity analysis assuming Qarmet JSC as the investor and excluding carbon credits.

Table VIII. Sensitivity analysis of financial model (Qarmet as project developer).

		Capex, $ mln					
		54.0	57.6	64.8	**72.0**	79.2	86.4
		-25%	-20%	-10%	**0%**	10%	20%
Electricity tariff, ¢/kWh	**3.00**	**-11.0**	**-14.1**	**-20.8**	**-27.7**	**-34.7**	**-41.6**
	3.50	1.6	-1.5	-7.7	**-14.0**	-20.2	-27.0
	3.75	8.0	4.9	-1.2	**-7.4**	-13.7	-20.0
	4.00	14.3	11.2	5.1	**-1.0**	-7.3	-13.5
	4.30	21.8	18.8	12.7	**6.5**	0.4	-5.8
	4.50	26.8	23.7	17.6	**11.5**	5.4	-0.7

The project demonstrates lower sensitivity to capex variations compared to electricity prices. For instance, 10% increase in capex leads to 25% decrease in NPV (from minus $27.7 mln to minus $34.7 mln), suggesting a multiplier effect of 2.5, while 17% increase in electricity prices (from ¢3.0 to ¢3.5 per kWh) leads to 51% improvement in NPV, suggesting a multiplier effect of 3.0. Overall, positive NPV is achieved at electricity tariffs exceeding ¢4.30 per kWh (a rounded average of the 2023 renewable energy auctions), subject to capex ranging between $54 and $79 mln.

The CBA and sensitivity analysis revealed that social benefits, particularly CO2 emissions mitigation, constitute the project's primary value. This aligns with Kazakhstan's national policy objectives for diversifying its energy supply and developing alternative RE sources (as discussed in the Introduction section above). Given the dominance of social benefits, the findings suggest that the government of Kazakhstan should explore policy options to incentivize private sector participation in

CMM utilization projects. This could involve revising the benefit distribution scheme to create a more attractive investment environment.

3.2. Cash flow gaps analysis

Assessment of cash flow gaps represents a crucial aspect of CBA for private investors. This analysis determines whether a project can generate sufficient cash flow to service debt obligations, thereby indicating financial feasibility.

Fig. 3. below illustrates the four scenarios run in the financial model:

- Scenario 1: Excludes carbon allowances, with project financing secured via two 7-year USD-denominated loans at the interest rate of 7.3%;

- Scenario 2: Includes carbon allowances, with project financing via two 7-year USD-denominated loans at the interest rate of 7.3%;

- Scenario 3: Includes carbon allowances, with project financing via two 7-year green bond issues at the interest rate of 7.3%;

- Scenario 4: Excludes carbon allowances, but electricity prices adjusted to ¢4.3/kWh (an average level of the 2023 renewable energy auctions).

All scenarios assume Qarmet JSC acting as the sole investor, eliminating complexities associated with benefit distribution among multiple private investors.

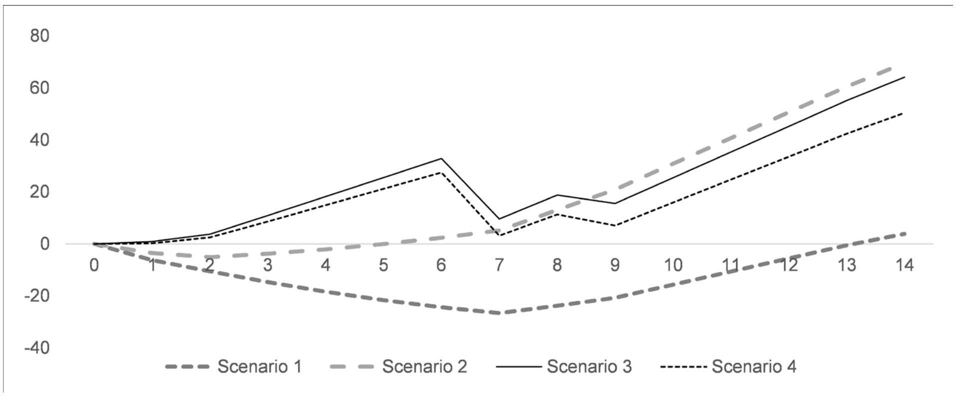

Figure 3. Cash flow gaps analysis ($ mln as of year-end).

The analysis reveals that financing through green bonds (Scenario 3 and 4) emerges as the most favorable option, because financing via loans leads to significant cash flow gaps. These findings suggest that the project's feasibility hinges on three critical conditions:

- Full benefit sharing: Qarmet should participate as both investor and developer. If Qarmet is not willing to engage in the project and allows third-party investors to implement it, the company should transfer all of its project benefits to such investors;

- Functional markets: The project requires access to a well-functioning local carbon market with available carbon allowance sales, or coal methane-based power plants should be allowed to participate in RE auctions, similar to biogas power plants. Comparison with similar studies support this need. For instance, Hummel et al. (2018) achieved IRRs of 20% and 28% for methane drainage at Indian collieries, while Nepsha et al. (2023) showed the 5.2-year payback period for CMM utilization at Kuzbass coal mines in Russia. In contrast, this study's model for Qarmet's project shows 12% IRR and 10-year payback period. These differences are mainly due to lower tariffs in Kazakhstan's heavily regulated energy market, compared to higher tariffs in Russia and India. Roshchanka et al. (2017) provides a more comprehensive discussion of the possibilities for state incentives to support the project;

- Green bond financing: Utilizing green bonds with their characteristic end-of-term repayment structure allows avoiding regular debt servicing burdens and should be seen as the most preferred option for the project's debt financing element, irrespective of its execution by Qarmet or third-party investors.

The cash flow gap analysis highlights the importance of strategic financing choices and favorable market conditions to ensure project viability for private investors in the context of methane capture projects.

4. Conclusion

This study aimed at conducting an exhaustive analysis of the Coal Mine Methane (CMM) Drainage and Utilization project in Kazakhstan, utilizing a detailed cost-benefit approach to evaluate its economic viability and environmental impacts. The findings demonstrate that incorporating carbon allowance sales substantially enhances the project's economics, demonstrating a promising net present value and internal rate of return. This financial upswing, marked by the increased NPV up to $15.6 mln and IRR up to 12.0%, illustrates the critical influence of carbon credits on the project's economic landscape.

However, a nuanced understanding of the study findings uncovers a critical challenge: in the context of current economic and policy conditions, the project's financial viability remains precarious for individual investors, evidenced by the residual negative NPV. This aspect of the findings points to the essential truth – the project's successful execution is heavily reliant on full engagement and support from the mine owner, i.e. Qarmet JSC. Without their active participation – in the form of self-financing or transferring all project monetary benefits to third-party investors – the financial model indicates the project may not achieve its intended objectives. This highlights the interconnected nature of financial feasibility and stakeholder involvement in environmental initiatives. To mitigate this risk, the government could also introduce measures such as securing stable electricity prices for methane-based power plants, enhanced carbon credit mechanisms, and targeted investment incentives to forge a more favorable investment climate.

Contributing to the broader discourse on sustainable energy development, this research provides key insights into the feasibility and benefits of CMM projects. It not only validates the economic and environmental viability of the CMM initiative in Kazakhstan's context but also presents a replicable model for similar regional or global efforts. The study offers a comprehensive framework for advancing sustainable energy solutions that align economic growth with environmental stewardship, informing policy, industry, and academic discussions.

Looking ahead, future research should delve into the socio-economic impacts of CMM utilization, assess the scalability of the technology in various settings, and examine the long-term effects of policy reforms on the RE sector. Investigating the development of advanced cost-effective technologies for methane capture and utilization remains a priority for enhancing global climate change mitigation efforts.

In sum, this paper underscores the CMM Drainage and Utilization project's potential as a contribution to Kazakhstan's energy and environmental strategy. By demonstrating the project's alignment with economic viability and environmental sustainability, alongside highlighting the crucial role of stakeholder participation, this study lays the groundwork for future endeavors aimed at fostering a sustainable and prosperous energy future.

Glossary

AMT: ArcelorMittal Temirtau
CARB: California Air Resources Board
CBA: cost-benefit analysis
CBM: coalbed methane
CCAC: Climate and Clean Air Coalition
CMM: coal mine methane
CPI: Consumer Price Index
DCF: Discounted Cash Flow
EC: European Commission
EDF: Environmental Defense Fund
GMP: Global Methane Pledge
GWP: Global Warming Potential
IEA: International Energy Agency
IRR: Internal Rate of Return
KEGOC: Kazakhstan Electricity Grid Operating Company

MAC: Marginal Abatement Cost
NPV: Net Present Value
O&M: operating and maintenance
RE: renewable energy
SCC: Social Cost of Carbon
SCF: Standard Conversion Factor
UNEP: United Nations Environment Programme
US BLS: United States Bureau of Labor Statistics
US EPA: United States Environmental Protection Agency
USDA: United States Department of Agriculture
VSL: Value of Statistical Life
WACC: Weighted Average Cost of Capital

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