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INNOVATION PROJECT VALUATION IN POTASH MINING: INDUSTRY 4.0/5.0 FRAMEWORK

Examined is the monetary valuation of innovation investments in potash mining and production – a strategically critical position in global fertiliser supply chains where the tools used to evaluate such investments have received surprisingly little systematic attention. Identified is the core challenge: the emergence of Industry 4.0 and the still-nascent Industry 5.0 has intensified capital allocation decisions, making robust valuation instruments more necessary than ever. Conducted is a structured narrative literature review supported by case evidence from Kazakhstan’s developing potash sector, notably the Satimola deposit project. Mapped are six primary valuation methods against the project lifecycle, with particular attention to how technological uncertainty shifts the relative merits of each approach. Developed is the Integrated Innovation Valuation Framework (IIVF), which combines Net Present Value (NPV), Real Options Analysis (ROA), Technology Readiness Level (TRL) gating, and balanced KPI dashboards into a five-phase decision-support structure. Demonstrated is that ROA and Monte Carlo simulation prove especially well-suited to early-stage Mining 4.0 investments, where managerial flexibility has genuine option value; ex-post KPI dashboards, meanwhile, become indispensable when Mining 5.0 logic requires capturing co-created social and environmental outcomes. Proposed is a framework intended to be actionable rather than merely theoretical — a practical tool for innovation managers, lenders, and policymakers working in potash and adjacent mining chemistry contexts.

Keywords: innovation valuation, Industry 4.0, Industry 5.0, potash mining, net present value, real options analysis, Kazakhstan, Mining 4.0, digital twins.

Кілт сөздер: инновацияларды бағалау, Индустрия 4.0, Индустрия 5.0, калий өндіру, таза келтірілген құн, нақты опциондарды талдау, Қазақстан, Тау-кен өнеркәсібі 4.0, сандық егіздер.

Ключевые слова: оценка инноваций, Индустрия 4.0, Индустрия 5.0, добыча калия, чистая приведенная стоимость, анализ реальных опционов, Казахстан, Горная промышленность 4.0, цифровые близнецы.

Introduction. The global potash market is predicted to progress steadily, escalating from USD 60.45 billion in 2023 to USD 90.49 billion by 2032, at a CAGR of 4.5% over the projection period. Agricultural applications are the primary impetus for potash demand, accounting for more than 93% of its end-use in 2024, . The drive to feed an exponentially increasing global population, thus propelling the use of fertilizers containing potash, motivates various producers, from legacy players to emerging entrants, to explore novel avenues to capitalize on throughout the extraction, processing, and distribution phases of the potash supply chain.

Compared to other aspects, what is still lacking is a set of adequate tools and methodologies to value innovation investments in monetary terms. Addressing this gap is more important than it seems: failure to do so may result in underinvestment in highly uncertain technologies, misallocation of investments along the different stages of a project, and a lack of transparency in communicating to external financiers the value of innovations alongside financial and ESG returns.

While Industry 4.0 is a well-established term associated with cyber-physical systems, Internet of Things, artificial intelligence, and digital technologies, these technologies have also a meaningful role in extraction and processing of minerals. The trend continues with calling Mining 5.0 human-centric smart production, rehabilitation of environment and harmonious coexistence between humans and machines in mines. Investments required for such transformations need to be properly evaluated.

Within global context of mining development, mineral-rich country of Kazakhstan is assessing potential of its potash resources. Estimates suggest that total exploration potential of these resources across the country may amount to 6.5–6.6 billion tonnes, with the largest reserves identified in the Chelkar and

Zhilyanskoe deposits located in West Kazakhstan. The article discusses the experience of Satimola deposit project with estimated annual output of 94,000 tonnes of potassium chloride and required financing amounting to USD 83 mln. Development of the country's chemical sector is also examined, growing by 12.5% in the first quarter of 2024 due to increased government support to fertiliser production by domestic manufacturers as part of import substitution strategy. However, the sector currently lacks fundamental analytical tools for making decisions.

Innovation valuation methods and tools in the traditional and resource industries have become increasingly more relevant in last years. In a vast number of cases, classical DCF methods, NPV and IRR primarily, are applied in order to evaluate and decide investments. At the same time, various limitations of this traditional approach have been stated in the literature, mostly when investment valuation of highly uncertain projects is in focus [2, 8]. One of the widely applied tools to evaluate the real options are Real Options Analysis methods, that try to assess the value of investment alternatives with some degree of flexibility. Furthermore, the use of so called TRL (Technology Readiness Levels) – frameworks, widely applied within industry and research collaboration, including NASA's technology maturity measurement for a series of technical functions [5], give a good opportunity to be used as a stage-gate framework for potash mining. What is missed today is an integrated approach for valuation of innovations throughout all lifecycle stages in mining sector of potash industry.

The paper is aimed at three objectives. The first objective includes a survey and critical assessment of prevailing monetary valuation methods of innovation projects in relation to highly capital-intensive mineral mining sectors. The second objective maps out the value drivers of Industry 4.0 and 5.0 technologies in potash mining. The third objective is to develop an Integrated Innovation Valuation Framework (IIVF) that synthesizes these tools in a stepwise stage-gated approach. The article is positioned as a conceptual and methodological contribution: it does not claim to present a complete DCF, NPV, IRR, ROA or Monte Carlo valuation of the Satimola project, because the required project-level cash flows, CAPEX and OPEX breakdown, discount rate, price assumptions and volatility parameters are not publicly available in sufficient detail.

Literature review. One of the most relevant and studied topics is the assessment of the monetary value of innovative projects in the field of potassium production. Researchers such as Zhironkin S., Ezdina N. have studied the transformation of the industry [14]. Seitkassimov G.S., Mussina A.A. noted changes in the production sector in terms of priorities for innovative development of the mining sector of Kazakhstan in the context of digital transformation [15].

A comprehensive literature search was organised across peer-reviewed academic publications, academic conference papers and proceedings, institutional reports, official statistical materials and selected industry publications. The search strategy focused on combinations of keywords such as innovation valuation, mining innovation, potash mining, real options analysis, NPV and IRR, Technology Readiness Level, Industry 4.0, Mining 4.0, Mining 5.0, digital twins, predictive maintenance, in-situ leaching and Kazakhstan mining sector. Sources were included when they were directly relevant to valuation methods, mining innovation, digital transformation in extractive industries or Kazakhstan's potash and chemical-sector context. Sources were excluded when their claims were promotional, insufficiently attributable or not connected to the valuation logic of the paper. Industry sources were retained only where they provided contextual or indicative benchmarks and were not treated as equivalent to peer-reviewed empirical evidence. Approximately 70% of the retained sources were published within the last five years (2021-2025), while older sources were used where they represented established valuation methods or widely recognised frameworks.

The main part. This research is based on a structured narrative literature review, with the purpose of forming a conceptual framework from reviewed data rather than testing hypotheses from primary data [3, 11]. A variety of quantitative, qualitative and case-study sources have been included in the review. A descriptive contextual case discussion of the potash sector in Kazakhstan has also been conducted to show where such a framework may be useful in practice.

The evaluation methodology of the framework consists of two connected stages: methodological and technological.

The first step of the methodology is a comparative analysis of different valuation methods. For each method of valuation, five criteria have been taken into account to identify advantages and disadvantages. These criteria are: 1) the main measurement metric of the method, 2) the theoretical advantages of the

valuation method, 3) the empirical limitations of the valuation method, 4) the field of application of the method and 5) the Technology Readiness Level (TRL) of the method.

In the second part, the gained insights are connected with Industry 4.0 and 5.0 innovations and their respective value drivers for potash mining, using cautious interpretation of international practice and Kazakhstan's sectoral context. These two layers are merged into the Integrated Innovation Valuation Framework (IIVF), which is designed as a phase-based decision-support framework rather than a stand-alone calculation model.

It is undeniable that the projects focused on the innovation differ from conventional capital investment projects in several ways that matter for valuation. Initially, the uncertainty is both higher and more structured (progressing through identifiable phases) in innovation projects, moreover, payoffs are frequently asymmetric, and a portion of the created value such as social and environmental, may not flow through market cash flows at all [2]. Table 1 summarises the principal methods identified in the literature review.

Table – 1

Comparison of Principal Monetary Valuation Methods for Innovation Projects

Method	Primary Metric	Strengths	Weaknesses	Best Suited For
Net Present Value (NPV)	Discounted cash flows	Time value of money; well understood; comprehensive	Static; ignores managerial flexibility; "now or never" bias	Mature, well-defined industrial projects
Internal Rate of Return (IRR)	Discount rate = zero NPV	Intuitive for ranking; useful in comparative contexts	Multiple IRR problem; reinvestment assumption questionable	Comparing alternative projects at pre-feasibility stage
Real Options Analysis (ROA)	Option value + static NPV	Captures flexibility; handles staged uncertainty; theoretically rigorous	Computationally complex; requires stochastic modelling inputs	Exploratory, phased, or R&D-intensive projects
TRL Scoring	Maturity score (1–9)	Standardised across sectors; tracks development milestones	Non-financial; qualitative; cannot replace DCF or ROA	Early-stage technology assessment and portfolio screening
Balanced Scorecard / KPI Dashboard	Multi-dimensional KPIs	Holistic; includes non-financial and ESG value	Subjective weighting; data-intensive; risk of gaming	Operational innovation monitoring; ex-post review
Monte Carlo Simulation	Probabilistic NPV distribution	Quantifies uncertainty; scenario-rich; supports ROA inputs	Requires well-specified probability distributions for inputs	High-uncertainty resource projects at feasibility stage

**Compiled by the authors based on sources [2, 4, 8, 9].*

The Net Present Value (NPV) approach is currently still the most widely used measure for investment appraisal globally. This approach calculates the present value of the (forecast) cash inflows and outflows of a project. In doing so, said cash flows are made anonymous by being discounted at a risk-adjusted rate, after which a positive result means that a project has a higher value than the cost of capital. If investment projects have a fixed cash flow profile, both NPV and IRR provide a clear decision guide, as proven by study results of Huang et al. [8] in established industrial contexts. An important limitation, however, is that this classic investment approach is static: it does not allow for the added value of waiting, of up- or downsizing of a project, or of switching to a completely different course of action as new information arises during the realization of a project. As highlighted by industry expert and former McKinsey partner,

“Innovation projects operate in fast-changing Industry 4.0 markets. Thus, an exclusively NPV-focused decision making represents a grave misjudgement and a core weakness in investment appraisal.”

Although NPV is still the preference for evaluation of investment opportunities in potash mining, the feasibility study for the Satimola deposit requires USD 83 million of financing, of which 30 per cent is equity and 70 per cent debt [6]. However, the static NPV approach does not capture the value of the option to develop the deposit in stages or alternatively to process the resource using in-situ leaching (ISL) instead of the traditional deep mining method. The ISL approach has much lower capital costs than the conventional mining method.

The Real Options Analysis (ROA) [4] tackles NPV’s basic shortfall by applying the logic of financial option pricing to real investment options. The extended value of the NPV (eNPV) equals the static NPV plus the value of options to make the right strategic investment decisions along the way as more information becomes available. Typically, there are four types of options available, such as the option to delay (wait for more data), the option to increase scope (to profit from a pilot), the option to reduce scope (to cut losses when returns are not adequate) and the so-called compound options that involve making a series of sequential decisions across several gates in a development portfolio.

Čirjevskis [4] proved that hybrid ROA approaches, built on Black-Scholes value formula, binomial lattice and Monte Carlo simulations methods, in dynamic environment outperform static DCF approaches. For investment in R&D projects Bhatnagar et al. [2] have proven that ROA provides higher (substantially higher) estimated value, because it captures benefits of possible upside. In case of potash mining innovation projects in Kazakhstan ROA is suitable for at least three decision nodes: 1) an option to postpone greenfield projects for Satimola resources until world market price for potash will recover; 2) an option to increase production capacity of ISL R&D project, if results of pilot wells will confirm possibility and economic efficiency of development of Akzhaik district deposits; 3) an option to choose technology – conventional mining or solution mining – for Satimola resources depending on results of drilling works.

TRL is a stage classification of the technology development maturity. The scale was originally developed by NASA and standardised for the Horizon Europe calls by the European Commission: from TRL 1 (fundamental research) to TRL 9 (product on market and industrialisation). In innovation governance TRL assessments are used as so called stage gates: projects shall have reached a certain maturity level in order to be ready for funding, integration in ongoing activities etc. The contribution to the monetary valuation of emerging technologies is mainly indirect, however: the position on the TRL scale influences the chosen discount rate and the probability of success, which are both integrated in Net Present Value (NPV) or Real Options Analysis (ROA).

Many major mining companies such as Rio Tinto, Newmont and BHP use variations of a TRL (Technology Maturity Assessment Models) to screen and prioritise portfolios of innovation opportunities. The difference in risk between a project at TRL 3 and TRL 7 must be reflected in the value that the project is expected to deliver. Bisogni in a recent paper proposed an extended innovation readiness level framework that combines a TRL with a readiness level for Market Readiness, Commercial Readiness and Innovation Maturity.

For the specific technologies of Mining 4.0 and 5.0 considered in this article, the value logic is grouped around three principal channels: cost reduction through operational expenditure savings, revenue growth through enhanced product quality and recovery, and risk reduction through improved safety, environmental and ESG performance.

Table – 2

Industry 4.0 and 5.0 Technologies in Potash Mining: Applications and Monetary Value Drivers

Technology	Application in Potash Mining	Estimated Value Driver	Evidence / Example
IoT Sensors & Real-Time Monitoring	Continuous monitoring of underground equipment, temperature, humidity, and gas levels	Potential reduction of unplanned downtime and improved safety compliance; the effect size is site-specific	Mining 4.0 literature and industry benchmarks [10, 11, 14]

Technology	Application in Potash Mining	Estimated Value Driver	Evidence / Example
Digital Twins	Virtual replication of mine process flows, conveyors, and processing plants	Indicative ROI potential of 20x-40x in selected process-level deployments; not an industry-average estimate	Bauer et al. [1]; Cranford [7]; Simio [12]
AI & Machine Learning	Equipment failure prediction, ore grade estimation and energy optimization where reliable operational data are available	Potential energy and recovery improvements; expected effect depends on data maturity and process stability	Zhironkin & Ezdina [14]; Moshkalo et al. [10]
In-Situ Leaching (ISL) Automation	Remote-controlled solution mining reduces surface footprint and capital expenditure	Lower capital intensity compared with conventional shaft mining in selected project settings; reduced environmental liability	Satimola Deposit, Kazakhstan [6]; Sánchez & Hartlieb [11]
Blockchain for Supply Chain	Immutable tracking of potash from mine to customer; ESG reporting transparency	Potential reduction of transaction and reporting costs; enhanced traceability for ESG-oriented finance	Zhironkin & Ezdina [14]; Cranford [7]
Autonomous Vehicles & Robotics (Mining 5.0)	Driverless haul trucks, automated drilling rigs, remote blasting	Potential operational-cost and safety benefits in suitable mining environments	Sánchez & Hartlieb [11]; Zhironkin & Ezdina [14]

**Compiled by the authors based on sources [1, 6, 7, 10, 11, 12, 14].*

Digital twin technology deserves particular attention. Bauer et al. [1] catalogued 32 real-life industrial applications of digital twins in mining, spanning collaborative decision-making, predictive maintenance, design validation, and production management. The six-layer architecture identified by Cranford [7], integrating IoT gateways, cloud repositories, virtual models, cognitive analytics, and operational outputs, gives a sense of the systemic depth involved. Simio [12] estimated that while Industry 4.0 platforms can achieve strong returns through IoT and big data integration, process-level digital twins may generate substantially higher returns through simulation-driven optimisation of scheduling, energy use, and maintenance windows. This range is included only as an indicative benchmark rather than as an industry-average estimate. The broader digital twin market (valued at USD 13.6 billion in 2024 and projected to grow at 41.4% CAGR toward USD 428 billion by 2034) does, however, signal genuine commercial momentum.

Kazakhstan's mineral economy is in a period of active transition. The country ranked first globally in uranium production in 2022 and is a leading producer of chromium, titanium, and potash . Chemical sector output exceeded 1 trillion tenge in 2023, and the government set a target to satisfy 80% of domestic fertiliser demand by end-2024 . The domestic potash deficit was running at around 95% during 2017–2021, which underlines the strategic logic of building indigenous capacity [6].

The Satimola project is the most advanced potash development currently underway in Kazakhstan, with planned annual production of 94,000 tonnes of potassium chloride and associated boric acid [6]. In 2024, the project operator Qazaq Kalium signed a memorandum of cooperation with KfW Bankengruppe and Euler Hermes Group, an important signal of confidence from Germany's development finance infrastructure . Kazakhstan's digital transformation trajectory, documented by Mukanov et al. and further contextualised by regional economic scholarship , creates institutional support for technology adoption in mining, though, as the World Bank [13] cautioned, gaps in digital geological data infrastructure and institutional coordination remain material obstacles.

No single valuation method handles the full complexity of a Mining 4.0 or 5.0 innovation project over its lifecycle. The IIVF responds to this by specifying different primary valuation instruments for different project phases, while maintaining coherence across the framework through TRL gating. Table 3 depicts the

five-phase progression and should be read as a conceptual phase-method matrix. In a project-specific valuation, each phase would require the collection of financial and technical inputs before producing numerical NPV, IRR, ROA or Monte Carlo outputs.

Table – 3

IIVF: Phase-Method Matrix for Mining 4.0/5.0 Projects

Evaluation Phase		Primary Method	Supporting Tools	Key Metrics	TRL Gate
Phase 1	Idea Screening	TRL Assessment + Scorecard	Expert panel; literature benchmarking	Technical feasibility score; strategic alignment index	1–3
Phase 2	Pre-feasibility	Static NPV; IRR	Sensitivity analysis; scenario modelling	NPV (base case); IRR; payback period; CAPEX estimate ±40%	4–5
Phase 3	Feasibility / Pilot	ROA (expanded NPV)	Monte Carlo simulation; binomial lattice	Expanded NPV; option value; volatility (σ); probability of success	6–7
Phase 4	Implementation	KPI Dashboard / BSC	Earned Value Management (EVM); milestone tracking	Cost variance; schedule variance; operational KPIs (downtime %, throughput, energy/t)	8
Phase 5	Post-implementation Review	Actual vs. projected NPV	ESG reporting; stakeholder audit	Realised NPV; CO ₂ abatement (t); safety incident reduction (%); jobs created	9

**Compiled by the authors based on sources [2, 4, 5, 8, 9, 11].*

Phase 1 (TRL 1–3) carries the highest uncertainty, with cash flow projections being speculative. A more relevant question for analysis would be whether the technology is feasible and aligns with the company’s competitive position on the market as well as general and sector-specific policies, including the government’s targets on import substitution in the fertilisers sector. The most appropriate decision support tool would be a structured scoring model that would enable to evaluate alternative options and to make decisions with the involvement of expert panels.

At Phase 2 (TRL 4-5), the project may provide sufficient technical and cost data to perform a static NPV calculation, although CAPEX estimates are still likely to carry a significant error margin and sensitivity analysis remains essential. In potash mining, the main value drivers are potash price, energy costs and ore grade. Energy price variability alone has the potential to change solution-mining operating costs substantially, as stated by the World Bank [13].

Phase 3 (TRL 6-7) is characterised by the implementation of a feasibility study, proof of concept or pilot project. At this stage, Real Options Analysis becomes useful because pilot results can inform whether to delay, expand, reduce or redirect the investment. Monte Carlo simulation can then be used to model probability-weighted NPV distributions by incorporating stochastic variables such as potash price, capital costs, ore recovery and energy consumption. These results can support internal decision-making as well as financing discussions with third parties [4, 9].

Phases 4 and 5 of project management focus on implementation control and realisation of value. Earned Value Management provides timely cost and schedule information to the project team. The post-implementation KPI dashboard must go beyond measurement of pure financial return. Mining 5.0 focuses on a human and ecological approach to value that reflects the metrics of importance to development finance institutions and ESG-focused investors, such as tonnes of CO₂ abatement, safety incident rates and mine employment. This is particularly relevant in the market conditions of Kazakhstan today.

Discussion. The IIVF is proposed as a conceptual application of valuation logic to the institutional and market conditions of Kazakhstan's potash sector. In this article, the Satimola deposit is used as an

illustrative sectoral context located between Phase 2 and Phase 3 of the development logic. The available public information makes it possible to discuss the relevance of DCF, ROA, TRL gating and ESG-oriented KPI dashboards, but it is not sufficient for a complete monetary valuation. Therefore, the paper does not present a final NPV, IRR, ROA or Monte Carlo result for Satimola. Instead, it shows how such a valuation could be structured once project-level cash flows, CAPEX and OPEX, discount rate, price scenarios, volatility estimates and probability assumptions become available. Within that logic, conventional shaft mining and ISL extraction methods represent alternative technological pathways whose relative value should be tested through the IIVF rather than assumed in advance.

Satimola is planning to attract financing in the form of KfW Bankengruppe participation. For this reason, the IIVF can inform a development-oriented investment assessment by linking financial value, technological maturity and ESG outcomes. Development banks and export credit agencies that support investments in emerging markets and transitioning economies increasingly require an overall valuation that goes beyond the classical DCF approach and includes environmental and social effects [13]. The IIVF's Phase 5 dashboard is designed to respond to this requirement. While Mukanov et al. reported on Kazakhstan's digital ambitions for development, previous studies on innovation management provided insight into the actual conditions in Kazakhstan with respect to transfers to the real sector, above all mining [15]. However, institutional problems concerning inter-ministerial coordination as well as digital geological data were identified as major challenges for mining [13]. Phase 1 strategic alignment assessment therefore has to respect these challenges.

The IIVF has three main limitations. Firstly, it is based on a structured narrative review and contextual case discussion rather than primary data from Kazakhstan or a quantitative meta-analysis of completed and abandoned potash innovation projects. Therefore, the validity of the framework should be tested in future empirical case studies. Secondly, estimated values for Industry 4.0 technologies, particularly the reported twenty- to forty-times returns for selected digital-twin deployments, are indicative and context-dependent. They should be read as benchmarks for identifying potential value drivers, not as guaranteed outcomes. Thirdly, this version of the IIVF does not explicitly model organisational and behavioural aspects of valuation, including cognitive biases in discount-rate selection and implementation barriers discussed in the broader innovation literature [2, 11]. Future research should therefore combine project-level financial modelling with organisational readiness analysis and more transparent sector-specific data.

Conclusion. The interface of innovation valuation methodology with Industry 4.0/5.0 technologies remains insufficiently explored within potash mining and chemistry. This article develops the IIVF as a conceptual decision-support framework for selecting appropriate valuation tools across the lifecycle of Mining 4.0 and 5.0 projects. None of the common valuation methods are suitable for every phase of such projects. While NPV and IRR remain necessary for financial discipline at the pre-feasibility stage, these methods can underestimate projects with high uncertainty and managerial flexibility. Real Options Analysis is theoretically more suitable for investments that unfold in stages and involve technology choices, while TRL categories serve as stage gates for selecting valuation methods and adjusting risk assumptions.

Second, Industry 4.0 and 5.0 technologies, such as IoT sensor networks, digital twins, AI-driven predictive maintenance and automation in in-situ leaching, create potential value drivers in potash mining and processing, including operational cost reduction, CAPEX reduction, safety improvement and ESG-related benefits. These value drivers need to be mapped and monetized step by step in the IIVF, using project-specific data rather than generic industry claims.

Kazakhstan's potash sector provides a relevant context in which the IIVF can be further tested. The Satimola project and the broader initiative to reduce the domestic potash deficit create an important opportunity for robust innovation valuation infrastructure. In the present article, Satimola is used to illustrate the decision logic of the framework; a full monetary valuation should be undertaken in future work when reliable project-level financial and technical data are available.

Potential areas for future research include empirical testing of the IIVF with live mining projects in Kazakhstan and comparable jurisdictions, deriving sector-specific volatility estimates for Phase 3 Monte Carlo inputs, and integrating the framework with ESG monetisation approaches increasingly required by development finance institutions in the region.

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КАЛИЙ ӨНДІРІСІНДЕГІ ИННОВАЦИЯЛЫҚ ЖОБАЛАРДЫ БАҒАЛАУ: INDUSTRY 4.0/5.0 ҚҰРЫЛЫМЫ

Андатпа

Зерттеуде тыңайтқыштардың жаһандық жеткізу тізбегінде стратегиялық маңызға ие калий өндіру және өңдеу саласындағы инновациялық инвестицияларды ақшалай бағалау мәселесі қарастырылған. Бұл салада мұндай инвестицияларды бағалау құралдарына қатысты жүйелі ғылыми зерттеулердің жеткіліксіздігі анықталды. Негізгі мәселе ретінде Industry 4.0 технологияларының дамуы және қалыптасу кезеңіндегі Industry 5.0 тұжырымдамасының енгізілуі капиталды бөлу жөніндегі шешімдердің күрделенуіне әкеліп, инновациялық инвестицияларды бағалаудың сенімді әдістеріне деген қажеттілікті күшейтетіні негізделді. Қазақстанның қалыптасып келе жатқан калий өнеркәсібі, оның ішінде Сәтімолә кен орны жобасы мысалында құрылымдалған нарративтік әдебиеттерге шолу және практикалық жағдайларды талдау жүргізілді. Инновациялық жобаның өмірлік циклі кезеңдері бойынша алты негізгі бағалау әдісі жүйеленіп, технологиялық белгісіздік жағдайында олардың салыстырмалы артықшылықтарының өзгеруі айқындалды. Таза келтірілген құн (NPV), нақты опциондар әдісі (ROA), технологиялық дайындық деңгейлері (TRL) бойынша кезеңдік бағалау және теңгерімді негізгі тиімділік көрсеткіштері (KPI) жүйесін біріктіретін бес кезеңді шешім қабылдауды қолдау құрылымы ретінде Инновациялық инвестицияларды интеграцияланған бағалау жүйесі (Integrated Innovation Valuation Framework – IIVF) әзірленді. Зерттеу нәтижелері нақты опциондар әдісі мен Монте-Карло модельдеуінің басқарушылық икемділіктің жоғары құндылығы тән «Тау-кен өндірісі 4.0» технологияларының бастапқы кезеңіндегі инвестицияларды бағалау үшін ерекше тиімді екенін көрсетті. Сонымен қатар, «Тау-кен өндірісі 5.0» тұжырымдамасы аясында бірлесіп қалыптастырылатын элеуметтік және экологиялық нәтижелерді бағалау мақсатында жобаны іске асырғаннан кейінгі теңгерімді KPI жүйесінің маңыздылығы дәлелденді. Ұсынылған құрылым тек теориялық үлгі ретінде емес, калий өнеркәсібі мен соған сабақтас тау-кен химиясы салаларында қызмет ететін инновациялық менеджерлердің, қаржы институттарының және мемлекеттік саясатты әзірлеушілердің практикалық қолдануына арналған шешім қабылдау құралы ретінде ұсынылды.

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ОЦЕНКА ИННОВАЦИОННЫХ ПРОЕКТОВ В ДОБЫЧЕ КАЛИЯ: СТРУКТУРА ДЛЯ ИНДУСТРИИ 4.0/5.0

Аннотация

В статье рассматривается денежная оценка инвестиций в инновации в сфере добычи и производства калийных удобрений — стратегически важной отрасли в глобальных цепочках поставок удобрений, где инструментам оценки таких инвестиций уделяется на удивление мало внимания. Выявлена основная проблема: появление «Индустрии 4.0» и зарождающейся «Индустрии 5.0» усложнило принятие решений о распределении капитала, в связи с чем надежные инструменты оценки стали как никогда необходимы. Проведен структурированный обзор литературы, подкрепленный примерами из развивающегося калийного сектора Казахстана, в частности проекта по разработке месторождения Сатимолы. Представлены шесть основных методов оценки в зависимости от жизненного цикла проекта, при этом особое внимание уделяется тому, как технологическая неопределенность влияет на преимущества каждого подхода. Разработана интегрированная система оценки инноваций (Integrated Innovation Valuation Framework, IIVF), которая объединяет чистую приведенную стоимость (Net Present Value, NPV), анализ реальных опционов (Real Options Analysis, ROA), определение уровня готовности технологии (Technology Readiness Level, TRL) и сбалансированные панели ключевых показателей эффективности в пятиэтапную структуру поддержки принятия решений. Доказано, что рентабельность активов и метод Монте-Карло особенно хорошо подходят для инвестиций на ранних стадиях развития концепции «Горная промышленность 4.0», где управленческая гибкость имеет реальную опционную ценность. В то же время постфактумные панели ключевых показателей эффективности становятся незаменимыми, когда концепция «Горная промышленность 5.0» требует оценки социальных и экологических результатов, достигнутых совместными усилиями. Предлагаемая концепция призвана стать не просто теоретической, а практически применимой — это полезный инструмент для менеджеров по инновациям, кредиторов и политиков, работающих в сфере добычи калийных солей и смежных областях.

