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"methodology and intelligent computational decision-making tools for the effective development of the unified gas supply system"

Relevance of the research topic

At present, new research and organizational-technical challenges are emerging, driven by intensifying competition among natural gas-producing regions worldwide, the rapid development of renewable energy sources, and the large-scale shift to electric vehicles. The structure of fuel and energy resources (FER) and hydrocarbon feedstock reserves is deteriorating due to the rising development costs of new natural gas fields.

In this context, the priority is to develop new scientifically based technical, technological, and system-analytical solutions aimed at minimizing costs across the entire operational lifecycle of the Unified Gas Supply System (UGSS), as a part of the fuel and energy complex. This requires full capacity synchronization of gas production, transportation, and processing during the construction of new main gas pipeline systems and the modernization of the existing UGSS.

To ensure the effective development of the system, two key scientific challenges must be addressed: improving the methodology for assessing the energy and resource efficiency of long-term investment projects, and developing adaptive methods for project selection that account for various risk levels under conditions of uncertainty. The complexity of these challenges necessitates the extensive application of systems analysis, as well as modern artificial intelligence tools within the framework of the digital economy.

The aim of the research is to develop a methodology and intelligent computational tools for making system-analytical decisions regarding the effective development of the UGSS, as part of the Russian Federation's fuel and energy complex, taking into account the use of various types of FER and renewable energy sources, as well as the Government regulation policy.

To achieve this objective, the following interrelated scientific and technical tasks were formulated and solved:

1. Conduct an analytical review of major contemporary scientific research on

methods of system analysis and planning for the effective development of the Russian fuel and energy complex and the Unified Gas Supply System.

2. Develop a system-analytical method for assessing the potential for efficient natural gas consumption.

3. Develop a probabilistic-statistical method for forecasting natural gas demand for various consumer categories.

4. Develop a method for long-term forecasting of energy consumption for various regions of the world and regions of the Russian Federation.

5. Develop an agent-based simulation method for analyzing the balance of natural gas supply and demand.

6. Provide a scientific rationale for the specific application of artificial neural networks (ANN) for forecasting natural gas consumption. Perform a system analysis of the effectiveness of using different types of ANN models for gas consumption forecasting.

7. Develop a mathematical formulation and a solution method for the optimization problem of the integrated gas transportation system using an ANN model.

8. Develop a nomographic-analytical method for selecting cost-effective supplies of various types of gas-related fuels and energy resources along new routes.

9. Develop a combined method for computerized agent-based and ANN analysis of the operation of natural gas and gas condensate processing facilities.

10. Propose decision-making methods for assessing economic efficiency and selecting viable investment projects.

11. Propose a method for automatic development of material and energy balances for gas industry objects as complex chemical and energy technological systems.

12. Develop the architecture and operational modes for a software package complex for making system-analytical decisions on the effective development of the UGSS and for monitoring the operation of its major facilities.

13. Develop a method for optimal placement of calorific value monitoring stations for transported natural gas within the gas transportation system structure.

14. Practically apply the main results of the completed research development

activities in various strategic, technical and economic developments.

Scientific novelty of the research:

1. A system-analytical method for assessing natural gas consumption potential in the UGSS has been developed using exergy and thermodynamic efficiency analysis.

2. A probabilistic-statistical method for forecasting gas demand by consumer categories is proposed, based on project data and their development status.

3. A long-term energy consumption forecasting method for various regions, incorporating demographic indicators and specific energy use, has been developed.

4. An agent-based simulation method for analyzing gas supply–demand balance is proposed, modelling real market interactions taking into account socio-economic processes.

5. A methodology for developing various ANN models (using short time series, anti-overfitting techniques, and stochastic networks) is proposed, with a comparative analysis of their forecasting performance.

6. An integrated ANN model for complex gas transport systems has been developed, using physical informed neural networks for hydraulic/thermal calculations.

7. A nomographic-analytical method for selecting cost-effective supplies of gas-related energy form (LNG, synthetic fuel, methanol) along new routes has been developed.

8. A combined computer-based method for analyzing gas processing operations has been developed, using digital twins, agent-based simulations and ANNs for real-time decision-making.

9. A decision-making method for assessing investment project efficiency under uncertainty has been developed, accounting for gas industry specifics, costs, taxation, and regulations.

10. A system-analytical method for updating technical-economic indicators and monitoring UGSS investment projects has been developed, using automated data processing to ensure gas supply and minimize costs.

11. A facet-hierarchical method for automated material-energy balance compilation and solution for energy systems is proposed, identifying losses and their

impact on efficiency and safety.

12. A methodology for selecting rational comprehensive innovation projects for UGSS development is proposed, using scenario analysis, demand, and project timelines for prioritization.

13. A method for optimal placement of calorific-value monitoring stations along the gas transport system is proposed, enabling efficient gas flow distribution.

Practical significance of the research.

1. A software package for analyzing long-term strategies was developed and applied, implementing the UGSS supply organization methodology and ANN-based gas consumption forecasting.

2. A specialized package for collecting and processing big data was developed, providing reliable information on exploration, production, imports, and related economic indicators.

3. A package for analyzing UGSS facility operation was developed, used to determine optimal control actions in large-scale pipeline systems.

4. A simulation program for ANN-based gas transportation system modelling was created, addressing capacity adequacy, compressor station energy minimization, and demand smoothing via gas reserves.

5. A program for neural-network modelling and optimization of large pipeline systems was developed for engineering business process management.

6. A software suite for remote monitoring of geographically distributed hydrocarbon chain facilities was developed.

7. The decision-making methodology for gas supply organization was practically applied to diversify sales markets and assess delivery efficiency (cash flows, CAPEX, OPEX, taxes, etc.).

8. The methodology for decommissioning excess gas transport capacities was used, considering fixed asset utilization and long-term flow forecasts.

9. Capital investment calculations for gas production and transport were performed for separate ethane-containing gas deliveries, including costs and pricing.

10. A method for refined gas quality assessment during transport was proposed,

identifying measurement-limited segments.

11. A long-term peak gas balance methodology was used for decisions management; a strategy for reliable supply under peak demand was developed.

12. Research results were incorporated into curricula at Mendeleev University for master's and postgraduate programs in energy-saving processes, system analysis, and mathematical modelling.

13. Materials were also used at the State University of Management for bachelor's and master's programs in fuel-energy management and business.

The following main results of theoretical research of scientific and practical significance are submitted:

1. A methodology for analyzing the structure and operating modes of the UGSS as a unique, complex production-organizational-economic system, comprising a set of interconnected supply chain subsystems for natural gas production, transportation, processing, storage, and distribution.

2. A methodology for system-analytical decision-making on the organization and assessment of energy-resource-efficient natural gas supplies within the UGSS, taking into account demand for natural gas in different regions.

3. A methodology for developing various types of ANN models for forecasting the efficient consumption of natural gas, accounting for the state of the gas market and the economic efficiency of natural gas utilization.

4. Methods for comprehensive analysis of main gas transportation system facilities, employing regression models, ANN models, and digital twins.

5. A facet-hierarchical method for automated analysis and intelligent computational tools for optimizing the efficiency of the gas transportation system using various types of ANN models.

6. Methods for system-analytical decision-making on the selection of rational innovation projects aimed at the effective development of the UGSS.

7. A methodology for designing the architecture and operating modes of a software package suite for system-analytical decision-making on the effective UGSS development.