Deliverable report 4

AI and IAGEN Application Use Case

Energy Optimization in Vaca Muerta through Digital Twins and Generative Artificial Intelligence (IAGEN)

I. Introduction.

The Vaca Muerta formation, located in Argentina, has established itself as one of the largest shale gas and oil fields in the world, presenting significant growth prospects for hydrocarbon production. Its importance in the global energy landscape is growing, especially in a context where demand for natural gas and oil remains substantial.

The oil and gas industry has an opportunity to optimize its operations, driven by the need to improve economic efficiency, comply with increasingly stringent environmental regulations, and adopt more sustainable practices. Energy optimization becomes a critical factor to ensure the competitiveness and long-term viability of operations in Vaca Muerta.
In this context, Digital Twins, Generative Artificial Intelligence (GAI), and AI agents are emerging as disruptive technologies with significant potential to transform the way energy companies operate, monitor, and manage their assets.

Digital Twins offer the ability to create virtual replicas of physical assets and processes, enabling real-time simulation and analysis to identify areas for improvement and optimization.

On the other hand, Generative Artificial Intelligence, with its ability to generate models, analyze large volumes of unstructured data, and optimize complex processes, presents new avenues for innovation and efficiency in the energy industry. The strategic combination of these two technologies has the potential to unlock unprecedented levels of energy optimization in the Vaca Muerta region, contributing to more efficient, safe, and sustainable production.

II. Digital Twins: A Virtual Model for Optimization in Vaca Muerta

Digital Twin technology involves creating a dynamic virtual representation of a physical asset, process, or system. This virtual replica is powered by real-time data from sensors in the physical world, enabling continuous monitoring of its performance, health, and environmental impact. Key components of a Digital Twin include a network of sensors and IoT devices for data collection, connectivity platforms for data integration, analytics capabilities for information interpretation, and modeling and simulation tools for behavior prediction.

In the oil and gas industry, Digital Twins offer a wide range of applications relevant to operations in Vaca Muerta.

One of these is monitoring and managing the integrity of critical assets and infrastructure, such as pipelines, production platforms, and refineries. By providing a virtual copy of these assets, operators can monitor their condition, detect early signs of failure, and identify opportunities for improvement. This leads to the implementation of predictive maintenance strategies, reducing costs associated with unplanned downtime and increasing equipment uptime.

Reservoir and process simulation using Digital Twins also facilitates production optimization . By creating virtual environments to test new systems and refine operational workflows with minimal risk, companies can maximize efficiency, increase productivity, and reduce costs at all stages of the oil and gas value chain .

Safety is another area where Digital Twins provide significant value. The ability to simulate risky scenarios and provide virtual training in a safe environment allows companies to improve safety procedures and emergency preparedness .

Furthermore, Digital Twins play a crucial role in optimizing energy consumption and resource management. By analyzing production and consumption patterns in virtual models, companies can identify inefficiencies, minimize waste, and optimize energy use.

The implementation of Digital Twins has already proven successful in various case studies within the energy industry.

III. Generative Artificial Intelligence: Driving Optimization and Innovation in Vaca Muerta

Generative Artificial Intelligence (GENI) is a branch of artificial intelligence that focuses on creating new content, such as models, images, code, or text, from existing data. This technology uses advanced algorithms to analyze large amounts of information, identify patterns, and generate new and original content that is often indistinguishable from human-created content. In the oil and gas industry, GENI presents enormous potential for optimization and innovation in Vaca Muerta.

Technological Synergy: Integrating Digital Twins and IAGEN for Advanced Optimization in Vaca Muerta

1. Prediction and optimization of energy consumption in real time

How does IAGEN help?

It uses large volumes of historical and current data (temperature, pressure, flow, pump usage, etc.) to generate predictive models and personalized recommendations that optimize energy use in wells and treatment plants.

Role of the digital twin:

The digital twin of each well or plant receives this data, simulates scenarios, and allows recommendations to be validated before being applied in the real world, with automatic adjustments in real time.

2. Reengineering of extraction and compression processes

How does IAGEN help?
It analyzes operational logs and generates optimized workflows, eliminating redundant or poorly synchronized steps that waste energy (e.g., frequent equipment startups/shutdowns).

Role of the digital twin:
It simulates new processes before their actual implementation, estimating energy savings and efficiency achieved, and allows for testing edge or failure conditions.

3. Predictive energy maintenance

How does IAGEN help?
It analyzes sensor logs and fault history and suggests interventions just before equipment becomes energy inefficient or deteriorates.

Role of the digital twin:
It simulates the behavior of equipment with different levels of wear and allows for anticipating how this would affect its energy efficiency.

4. Evaluation and recommendation of carbon footprint reduction strategies

How does IAGEN help?
It automatically generates reports on the main sources of consumption and emissions at each stage (extraction, processing, transportation) and proposes mitigation or compensation measures (use of renewable energy, carbon capture, etc.).

Role of the digital twin:
It calculates the estimated impact of each strategy before its implementation, and enables virtual monitoring of the energy and decarbonization plan.

5. Identification of invisible energy leaks

- Activity: The entire chain (production, midstream, internal distribution)

- IAGEN + digital twin:
    - IAGEN analyzes historical data and generates hypotheses about undetected leaks, such as thermal leaks, miscalibrated valves, and electrical leaks.
    - The digital twin can test these hypotheses virtually without stopping the operation.

6. Additional use cases:

The combination of Digital Twins and Generative Artificial Intelligence represents a powerful synergy that can unlock new frontiers in energy optimization at Vaca Muerta. The integration of these two technologies enables more advanced and holistic optimization of operations in the oil and gas industry.

One way this synergy manifests itself is through the use of real-time data from Digital Twins to train and improve IAGEN models. Digital Twins provide a constant stream of updated information on the health and performance of physical assets and processes. This information can be used by IAGEN algorithms to learn and adapt to changing conditions at Vaca Muerta operations, resulting in more accurate predictive models and more effective optimization strategies.

Furthermore, IAGEN can generate optimized operating scenarios that can then be simulated and evaluated within the virtual environment provided by Digital Twins. This allows companies to test different strategies and configurations with minimal risk, identifying the most efficient solutions to improve performance and reduce costs at Vaca Muerta.

The combination of both technologies also leads to advanced predictive failure analysis and maintenance optimization. Digital Twins continuously monitor equipment health, while the IAGEN analyzes this data to accurately predict when failures are likely to occur. This capability allows companies to proactively schedule maintenance, minimizing downtime and reducing costs associated with unplanned repairs.

Finally, the IAGEN can analyze the large volumes of data collected by the Digital Twins and generate useful, real-time insights for operators at Vaca Muerta. This facilitates faster and more informed decision-making, leading to greater efficiency and productivity in operations. The ability to achieve closed-loop optimization, where data from the Digital Twin feeds the IAGEN model, which in turn generates recommendations to optimize the physical system, exemplifies the power of this integration

Area of Application	Digital Twin Approach	Generative Artificial Intelligence Approach	Synergistic Benefits
Asset Integrity Management	Real-time monitoring of infrastructure health, stress and wear simulation.	Sensor data analysis for anomaly detection and prediction of potential failures.	Early identification of potential problems, proactive maintenance scheduling, and extended asset lifespan.
Production Optimization	Simulation of reservoir behavior,	Generation of optimal drilling	Improved recovery rates,

	optimization of extraction rates and processes.	strategies, advanced analysis of production data.	improved well productivity, optimized resource allocation.
Predictive Maintenance	Continuous monitoring of equipment performance, prediction of maintenance needs.	Generation of maintenance programs, equipment fault diagnosis, and repair guidance.	Highly accurate failure prediction, optimized maintenance programs, reduced downtime and maintenance costs.
Safety and Risk Management	Simulation of emergency scenarios, virtual training for safety procedures.	Analysis of operational data for hazard identification and generation of risk mitigation	Enhanced safety protocols, improved emergency response capabilities, and reduced accident and

		strategies.	incident rates.
Energy and Resource Management	Monitoring energy consumption, simulating energy-saving strategies.	Identification of energy waste patterns, optimization of energy use.	Reduced energy consumption, waste minimization, improved resource efficiency, and contribution to sustainability goals.
Supply Chain Optimization	Tracking the flow of materials and equipment, simulating logistics scenarios.	Predicting supply chain disruptions, optimizing transportatio n routes.	Improved logistics, reduced transportatio n costs, timely availability of resources, minimization of disruptions.

IV. AI Agents and Agentic Flows for Implementation

1. **IAGEN Agents Concept**

In recent years, generative artificial intelligence (GAI) has revolutionized the way we interact with technology, enabling the development of systems capable of generating content, answering complex questions, and assisting with highly demanding cognitive tasks. From this capability, a new technological architecture has emerged: GAI-powered agents. These agents are not simple conversational interfaces, but autonomous systems that can interpret instructions, make decisions, execute tasks, and learn from their interactions with the environment.

An IAGen agent combines large language models with additional components such as external tools, memory, planning, and autonomous execution. This allows them to operate in complex environments, with the ability to break down objectives into steps, coordinate multiple actions, interact with digital systems (such as databases, APIs, or documents), and adapt to context changes in real time. These qualities distinguish them from traditional chatbots and open up a range of more sophisticated and customizable applications.

At the organizational level, these agents are being used to automate processes, generate data analysis, assist in decision-making, and improve the user experience, both internally and externally. For example, they can take on human resources, legal, financial, or logistics tasks, and even tasks linked to the technical areas of production processes, acting as intelligent assistants that collaborate with human teams. This ability to integrate knowledge and execute tasks autonomously transforms the way organizations can scale their operations without losing quality or control.

Furthermore, agentic workflows—structures where multiple agents collaborate to solve complex problems—allow responsibilities to be distributed among different agent profiles, each with specific functions. This creates hybrid work environments where humans and agents coexist, optimizing time, costs, and results. The ability to connect agents with tools such as Google Drive, CRMs, or document management platforms further expands their capabilities.

The development of IAGen-powered agents represents a crucial step toward a new era of intelligent automation.

Among the benefits of authentic workflows powered by generative AI models is the ability to automate entire production processes, end-to-end, and even add value by leveraging the capabilities of language models based on these technologies.

However, its implementation also poses technical, ethical, and legal challenges, ranging from responsible design to human oversight. Therefore, understanding its architecture, operational logic, and potential impacts is critical for its effective and safe adoption in diverse professional contexts.

2. Agent design proposal for energy optimization with digital twins

a. **See what's happening**
The agent receives data from the well or plant: temperature, pressure, how much energy the pumps are using, etc.

b. **Remember what happened before**
You also have access to historical data, for example, when the most energy was spent or when production was most efficient.

c. **Imagine different possible scenarios**
Use an “artificial brain” type model to *generate* different ways of operating (for example, changing the speed of a pump).

d. **Simulate before acting.**
Ask your digital twin: “If I operate like this, will I use less energy?” The twin is like a virtual well or plant that simulates what would happen.

e. **It chooses the best option and applies it**

When it finds the most efficient way, **it sends that instruction to the real system** (or suggests to the human operator that it be applied).

f. **He learns all the time.**
If the decision was good, he learns from it. If it wasn't, he adjusts to do better next time.

3. Hypothetical example:

At a gas compression plant in Vaca Muerta, a digital twin integrated with IAGEN predicts energy consumption based on demand and adjusts operations to avoid overloads, resulting in 18% savings in annual energy costs.

4. Detailed description of the phases, techniques, and different strategies for implementing AI agents and agentic workflows powered by IAGEN in combination with digital twins.

1. **AI Agent Workflow powered by IAGEN**

a. **Energy forecast**

- Use generative *LLM models + a Time Series Forecaster* to estimate future consumption based on current variables. A Time Series Forecaster is a tool that uses past data to predict what will happen in the future. For example, a plant records how much energy was used each day. The Time Series Forecaster analyzes that data and tries to predict how much energy will be used tomorrow or next week. In the context of this report, it is used in conjunction with a Large Language Model (LLM) to estimate future energy consumption in different parts of an operation, such as a well, a pump, or a plant, based on current variables.
- Create reports of expected consumption by operating unit (well, pump, plant, etc.).

b. **Generative optimization**

This section addresses "Generative Optimization," a key system function that uses Generative Artificial Intelligence (GENI) to identify and propose optimal operating configurations. This includes optimizing flow rates, pump speed and frequency, and valve pressures, all with the goal of maximizing energy efficiency in Vaca Muerta's operations.

Generates optimal operating configurations for:

- Flow rate. This refers to the volume of fluid (whether oil, gas, or water) flowing through a point in a given period of time. Optimizing flow rates involves finding the right balance to maximize production without overloading the system or wasting energy. This may include adjusting pump speed or valve opening to maintain a constant and efficient flow.
- Pump speed and frequency. Pump speed refers to how fast the impeller rotates, while frequency refers to the number of times the pump is turned on and off in a given period. Optimizing these parameters involves finding the settings that allow the required fluid to be pumped with the lowest possible energy consumption. This may include varying the pump speed based on demand or scheduling the on/off cycles to avoid unnecessary energy spikes.
- Valve pressures. Valves control the flow of fluids in a system by opening or closing. In turn, the pressure at which they operate is crucial. Optimizing valve pressures involves adjusting the valve opening to maintain the desired pressure at different points in the system. This helps reduce or avoid pressure fluctuations that can damage equipment or reduce efficiency, and can also help minimize leaks and energy waste.

- Generates prompts to digital twin simulators to test each configuration.

The IAGEN model or an AI agent automatically creates specific prompts or instructions for the digital twin simulators. These prompts are essentially questions or requests designed to test different operating configurations proposed by the IAGEN. For example, the IAGEN might generate a prompt that says, "Simulate the impact on energy consumption if we increase the flow rate of pump X by 15% and reduce the pressure of valve Y by 10%." The digital twin then runs this simulation, providing data on the resulting energy consumption, efficiency, and other relevant factors.

In the context of Vaca Muerta, this could mean that IAGEN analyzes historical and current data from an oil well and generates a prompt for the digital twin that simulates how changing pumping speeds at certain times of the day would affect production and energy consumption. The digital twin, which is a virtual replica of the well, runs this simulation and provides detailed results, allowing operators to evaluate whether the proposed configuration is viable and efficient before implementing it in the real world.

c. Automatic simulation

Following the "Generative Optimization" phase, where IAGEN proposes operating configurations, "Automatic Simulation" is activated as a crucial validation mechanism. This stage uses the digital twin to virtually test the proposed scenarios, focusing on evaluating energy performance without the need for physical interventions in the actual system.

Description of the scenarios:

Scenario transfer to the digital twin : IAGEN sends multiple alternative configurations to the digital twin, each with specific settings for operating variables. The digital twin, acting as an isolated test environment, simulates the system's behavior under each of these configurations.

Energy Performance Benchmarking : The digital twin processes each scenario, generating detailed data on energy consumption and efficiency. These results are then comparatively analyzed to identify the configuration that offers the best balance between efficiency and performance.

Optimal configuration selection and recommendation : Once the simulations are complete, the system selects the configuration that has demonstrated the best energy performance. This optimal configuration is presented as the recommendation for implementation in the real system, based on the virtual validation performed.

d. **Real-time decision-making and adjustments**

It is key to develop and implement the integrated Digital Twin and Generative Artificial Intelligence (GAGI) system's ability to dynamically react to variations in operating conditions. Variations such as weather, pressure, and demand update the operating plan. Here, real-time information collected by sensors and the Digital Twin is key, allowing GAGI or an AI agent to automatically adjust operating parameters to maintain energy efficiency. Hypothetical scenario: If there is a sudden change in demand for gas or oil, the system can modify pump speeds or valve pressures to optimize energy consumption. Additionally, the AI agent can suggest adjustments to the human operator, providing an additional layer of control and oversight. This ensures that operations at Vaca Muerta continuously adapt to changing conditions, maximizing efficiency and minimizing energy waste.

Continuous learning

The Digital Twin and Generative Artificial Intelligence (DGI) system should also incorporate dynamic learning and continuous improvement. This continuous learning process is essential to maintaining the system's efficiency and adaptability over the long term. Model adjustments can be made weekly or monthly, considering the following factors:

- “Deviations between prediction and reality”:
    - The AI agent, or IAGEN, constantly compares energy consumption and performance predictions with actual data observed in operations. If there are significant differences between predictions and actual results, the system adjusts its models to reduce these deviations in the future. For example, if the model underestimated energy consumption by 10% last week, it will recalibrate to account for this error and improve accuracy in future predictions.
- Feedback from the real system or the digital twin:
    - The system receives feedback from both the real system (through sensors and operational data) and the digital twin (through simulations and tests). This feedback includes information on the actual performance of the implemented configurations, observed efficiency, and any detected issues or anomalies. The system uses this information to fine-tune its models and improve its prediction

and optimization capabilities. For example, if the digital twin detects an unexpected spike in energy consumption during a simulation, this information is used to refine the model and prevent similar situations in the future.

- New configurations that emerged spontaneously:
    - Occasionally, human operators or AI agents' own recommendations may implement new or unplanned operating configurations. These configurations may arise in response to unforeseen situations or as a result of experimentation and the search for improvements. The system records these new configurations and analyzes their impact on energy performance. If a new configuration proves to be more efficient than previous ones, the system incorporates it into its models and considers it in future recommendations. For example, if an operator manually adjusts the speed of a pump and observes a significant improvement in efficiency, this new configuration is recorded and used to fine-tune the optimization model.

5. Concrete examples of software and systems with necessary integrations

System	**Function**
SCADA / IoT	Real-time data entry
Historian / DWH	Historical data for training
Digital twin platform (e.g. Siemens, Cognite, AspenTech)	Scenario simulation
Recommendation Engine / Control API	Applying the suggested settings

Visualization platform (e.g., Grafana, Power BI, Custom Dashboard)	Show insights and decisions

V. Challenges and Opportunities for Implementation in Vaca Muerta

Challenges

The implementation of Digital Twins, AIGEN, and AI agents in Vaca Muerta presents significant challenges and opportunities. On the technical front, integrating these technologies with existing infrastructure and legacy systems can be complex.

The management and quality of the large volumes of data generated also represent a significant challenge, requiring specialized expertise.

Cybersecurity and the protection of sensitive information are crucial, given the interconnectedness of virtual and physical systems.

Furthermore, the scalability of technological solutions to cover the entirety of Vaca Muerta operations is an aspect that must be carefully considered.
From an economic perspective, the high initial investment costs in hardware, software, and infrastructure can be a barrier to adoption. Therefore, it is essential that companies can demonstrate a clear and tangible return on investment to justify these expenses.

Regarding regulatory and talent challenges, the specific regulatory framework in Argentina for the adoption of Digital Twins and AIGEN in the oil and gas industry is still in its infancy, which may be an additional barrier to adoption. The level of complexity we noted suggests the involvement of companies or laboratories specialized in this type of development, which would reduce the initial learning cost.

Likewise, the availability of human talent with specialized skills in data science, artificial intelligence, and digital technologies applied to the energy sector is a critical factor for the success of the implementation.

Opportunities

Despite these challenges, the opportunities offered by Digital Twins and IAGEN for energy optimization in Vaca Muerta are considerable.

These technologies have the potential to generate significant increases in operational efficiency and productivity.

Reducing operating and maintenance costs through predictive maintenance and process optimization is another key benefit.

Improving safety and reducing operational risks are also key areas where these technologies can add value.

Finally, the implementation of Digital Twins combined with IAGEN and AI agents can contribute to the sustainability and reduction of the carbon footprint of operations in Vaca Muerta, aligning with the growing environmental and regulatory demands.

VI. Strategic Recommendations and Conclusions

For Vaca Muerta operating companies wishing to address the implementation of Digital Twins and IAGEN for energy optimization, it is recommended to focus on pilot projects to demonstrate value and develop internal expertise.

Establishing robust data governance frameworks is crucial to ensuring data quality and security. Investing in training and upskilling programs for existing staff is essential to closing the talent gap.

Before large-scale implementation, clear objectives should be defined and specific use cases identified. Fostering collaboration between information technology (IT) and operational technology (OT) teams is critical to successful integration.

It is suggested to adopt a phased implementation approach, starting with high-value applications.

Finally, collaborating with technology providers and partners with relevant expertise can facilitate the adoption process.

It is recommended to analyze the possibility of investing, in the short term, in AI agent implementation teams, technology, and training.

Investment in proofs of concept and pilot testing is required. The focus here must be on developing the talent needed to implement the solution, as there is a trend toward cost reduction in systems that enable "no-code" and "low-code" automation. For the first stage, it is also recommended to recruit teams with experience in the design and implementation of AI agents. Finally, it is key to form an in-house team to support and foster an agentic culture that redefines human-machine interaction.

For the Argentine government and regulatory bodies, it is recommended that clear regulatory guidelines for the use of Digital Twins and AI in oil and gas operations be developed to foster investment and innovation. Promoting educational programs to develop talent in data science, AI, and digital technologies relevant to the energy sector is a long-term measure that can ensure the success of digital transformation.

In conclusion, the strategic implementation of Digital Twins and Generative Artificial Intelligence and AI agents in Vaca Muerta offers significant transformative potential for energy optimization. Key benefits include substantial gains in operational efficiency and productivity, a considerable reduction in operating and maintenance costs, a notable improvement in safety and reduction of operational risks, a significant contribution to sustainability and carbon footprint reduction, and enhanced capabilities for decision-making and strategic planning.

Despite the challenges, the synergy between these technologies presents a unique opportunity to drive efficiency, safety, and sustainability in the oil and gas industry in the Vaca Muerta region.

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