



TESTING CENTER FOR OIL AND GAS LEMIGAS

SCIENTIFIC CONTRIBUTIONS OIL AND GAS (SCOG)

Vol. 49. No. 3, September: 723 – 743 - <https://journal.lemigas.esdm.go.id>

ISSN: 2089-3361, e-ISSN: 2541-0520

Published by:

LEMIGAS

Multi-Stakeholder Agent-Based Decision Framework for Sustainable Horizontal Well Placement: Field Validation of Ultra-Deep Azimuthal Resistivity Integration Across Three Well Examples

Ida Bagus Gede Hermawan Manuaba^{1*}, Dermawan Wibisono¹, Manahan Parlindungan Saragih Siallagan¹, Taufan Marhaendrajana², and Haifeng Wang³

¹*School of Business and Management, Institut Teknologi Bandung,
Ganesa Street No. 10, Bandung, West Java, Indonesia.*

²*Teknik Perminyakan, Institut Teknologi Bandung,
Ganesa Street No. 10, Bandung, West Java, Indonesia.*

³*SLB,
Dammam, Eastern Province, Saudi Arabia.*

*Corresponding author: Ida Bagus Gede Hermawan Manuaba (idabagusghm@gmail.com)
Ida Bagus Gede Hermawan Manuaba: Orchid id: <https://orcid.org/0009-0001-2985-710X>

Received: 23 April 2026; Revised: in revised form 06 August 2026; Accepted: 11 September 2026
Available: online 30 September 2026.

ABSTRACT - The oil industry is under mounting pressure to reconcile economic viability with environmental sustainability while managing complex stakeholder dynamics. Traditional modelling approaches struggle to capture emergent behaviours from multi-agent decision-making in sustainable oil recovery (Bonabeau, 2002; Macal & North, 2010). Three field wells are examined through an economic review within an agent-based framework that integrates Ultra-Deep Azimuthal Resistivity (UDAR) technology with 3D far-field petrophysics to optimize sustainable oil recovery by improving stakeholder collaboration (Manuaba et al., 2025a). We developed a multi-agent system comprising nine stakeholder types of petrophysicists, drilling engineers, geologists, reservoir engineers, oil operators, service companies, government regulators, oil market analysts, and geopolitical forces that incorporate UDAR's 3D far-field characterization capabilities. The model examines four critical points: economic feasibility, environmental impact, technical risk, and political stability. An agent-based framework illustrates how UDAR technology serves as a central information hub, facilitating informed decision-making across technical, business, and regulatory domains (Manuaba et al., 2024; Pewekar et al., 2025). The model captures complex feedback mechanisms, including market signals, regulatory alignment, technology integration loops and human interactions. Sustainability metrics, such as well lifespan, energy efficiency, social impact, economic viability, and resource conservation, are embedded in agents' decision-making processes (Erhueh et al., 2023). Results show that integrating UDAR technology with agent-based provides a robust framework for optimizing sustainable oil recovery operations. This approach enables coordinated stakeholder action while balancing competing objectives and adapting to dynamic market and regulatory conditions, offering significant potential for improving both economic and environmental outcomes.

Keywords: sustainable oil recovery, energy policy, agent-based, drilling risk, UDAR technology, 3D far-field petrophysics.



How to cite this article:

Ida Bagus Gede Hermawan Manuaba, Dermawan Wibisono, Manahan Parlindungan Saragih Siallagan, Taufan Marhaendrajana, and Haifeng Wang, 2026, Multi-Stakeholder Agent-Based Decision Framework for Sustainable Horizontal Well Placement: Field Validation of Ultra-Deep Azimuthal Resistivity Integration Across Three Well Examples, *Scientific Contributions Oil and Gas*, 49 (3) pp. 723-743.

1. Introduction

The global oil sector now operates in an environment shaped by diverse stakeholders, competing objectives, and evolving regulatory frameworks (Höök & Tang 2013). Traditional approaches often miss the interconnected technical, economic, and policy dimensions that influence project outcomes. Recent advances in subsurface characterization, particularly Ultra-Deep Azimuthal Resistivity (UDAR) logging, create opportunities to enhance reservoir understanding and decision-making (Manuaba et al., 2025a). UDAR systems provide deep-investigation resistivity measurements that reveal geological features extending far beyond the borehole, supporting improved geo-steering, pay-zone identification, and enhanced oil recovery (EOR) decisions (Wu et al., 2023). Alongside these technological developments, the agent-based framework has become a powerful tool for analyzing complex socio-technical systems. It can simulate autonomous actors, technical teams, regulatory bodies, market forces, and geopolitical players whose interactions produce system-level behaviours that deterministic models cannot capture. For oil recovery, agent-based models were particularly valuable for examining technology adoption, stakeholder coordination, and regulatory compliance within an integrated framework (Ringler et al., 2016). Integrating UDAR technology with Agent-Based therefore presents a promising approach for designing sustainable oil recovery strategies that account for both subsurface complexity and stakeholder heterogeneity.

1.1 Research motivation

Today's oil industry must strike a balance between economic performance and environmental sustainability. Increasingly stringent climate policies, stakeholder expectations, and regulatory mandates necessitate the adoption of more comprehensive decision-making frameworks (Höök & Tang 2013). Existing reservoir and economic models, while sophisticated, often fail to integrate environmental considerations and stakeholder constraints into operational planning. UDAR technology improves reservoir characterization and reduces operational uncertainty, but successful integration requires coordinated decision-making among multiple stakeholder groups with distinct priorities, informational inputs, and risk perceptions. Understanding these interactions is essential for designing sustainable oil recovery strategies that are both technically sound and socially acceptable (Clarkson 1995).

1.2 Research objectives

This study develops an integrated Agent-Based framework designed to:

- Represent interactions and decision processes of key oil-sector stakeholders
- Incorporate UDAR technology as a central data source affecting multi-agent decision-making
- Embed sustainability metrics, such as environmental, economic and social, into agent behaviours
- Evaluate trade-offs between competing operational, regulatory, and market objectives
- Explore scenario-based outcomes under varying technological, regulatory, and geopolitical conditions.

1.3 Paper Structure

The Literature Review section reviews prior work on agent-based modelling, UDAR technology, and sustainable recovery strategies. The Materials and Methods section outlines our methodology and agent-based framework, including the behavioural rules and interactions among agent classes. The Results section presents model implementation, scenario results, and field validation. The Discussion section addresses policy, industry, and sustainability implications. The Conclusions section presents recommendations and future research directions.

1.4 Literature review

Agent-based modelling has gained traction as a framework for analysing complex energy systems characterised by heterogeneous actors, decentralised decision-making, and dynamic feedback loops. Early Agent-Based Framework implementations focused on electricity markets and supply chain behaviour, showing the method's ability to capture emergent system properties from local-level interactions. These studies have revealed that traditional top-down approaches often overlook the adaptive behaviours and bounded rationality inherent in real-world energy systems (Bonabeau 2002).

As agent-based models matured, researchers applied them to broader energy contexts, including long-term planning, policy simulations, and operational efficiency. Applications in oil and gas expanded to refinery operations, maintenance scheduling, and production planning, where multi-agent coordination reduced inefficiencies and improved operational resilience (Basu 2017). Prior work demonstrates that agent-based frameworks are suitable for modelling socio-technical systems in which multiple stakeholders influence outcomes through iterative, interdependent decision-making, making them particularly appropriate for sustainable oil recovery analysis.

Ultra-Deep Azimuthal Resistivity (UDAR) technology represents a significant advancement in formation evaluation, enabling the detection of resistivity contrasts far beyond the wellbore (Manuaba et al., 2025a). Unlike conventional resistivity tools that rely on near-borehole measurements, UDAR systems deliver far-field petrophysical information, enabling operators to map geological structures, fluid contacts, and stratigraphic variations at substantially greater depth (Figure 1). Conventional resistivity, also known as propagation resistivity, can reach up to 4 ft, whereas UDAR resistivity can reach up to 100 ft.

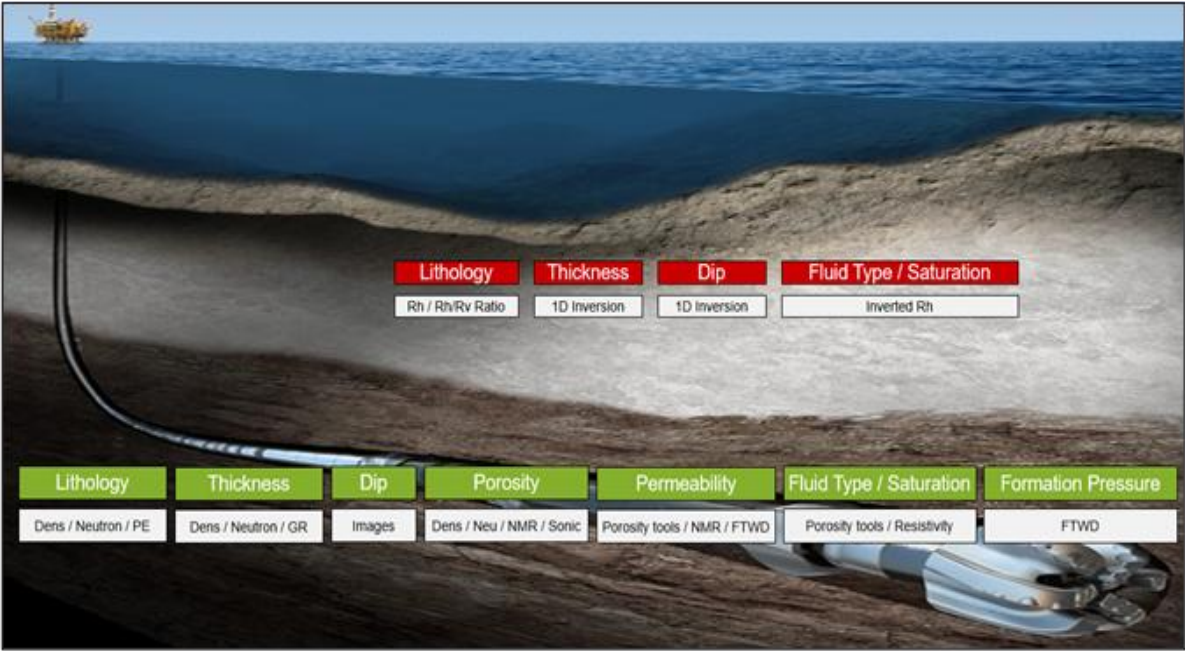


Figure 1.

Conceptual diagram illustrating the relationship between petrophysical properties and the measurements used to derive them, distinguishing near-field properties (green), resolved from conventional near-borehole logging, from far-field properties (red), which require UDAR—adapted from Manuaba et al. (2025a).

This enhanced detection is particularly valuable for real-time geo-steering, where continuous directional resistivity measurements support more informed well placement decisions. Examples show UDAR technology enhances the ability to identify bypassed pay zones, optimise lateral trajectories, and reduce drilling risks, particularly in complex or thinly laminated reservoirs (Ameneiro et al., 2023; Manuaba et al., 2024). Recent advances in inversion algorithms have further refined UDAR's resolution, enabling better structural and stratigraphic interpretation even in transitional resistivity environments.

Sustainable oil recovery has evolved from maximising hydrocarbon extraction to a holistic framework incorporating environmental, social, and governance (ESG) considerations (Elkington 1997). Traditional recovery approaches prioritised economic returns while giving limited regard to external environmental costs. However, increasing regulatory scrutiny and global climate commitments have shifted industry priorities toward sustainable operational practices (Bui et al., 2018).

Modern sustainable recovery strategies emphasise reducing emissions, minimising water consumption, improving energy efficiency, and integrating circular resource-use practices. Technological innovation plays a central role in this transition. Advanced reservoir characterization tools, such as UDAR, enable the more precise identification of productive zones, thereby reducing unnecessary drilling and associated emissions.

Oil recovery projects involve diverse stakeholders with distinct incentives, constraints, and decision processes. Technical stakeholders, geologists, reservoir engineers, and petrophysicists prioritize subsurface accuracy, operational safety, and technical feasibility. Business stakeholders, including operators and service companies, focus on profitability, market positioning, and investment efficiency. Regulatory entities emphasize compliance, environmental protection, and public welfare, while global markets and geopolitical forces influence oil prices, investment flows, and cross-border regulatory alignment.

Stakeholder theory suggests these actors exert varying degrees of influence depending on their power, legitimacy, and urgency. However, traditional optimization models often fail to capture the interactive and sometimes conflicting relationships among stakeholder groups. An agent-based framework addresses this gap by representing heterogeneous stakeholders with unique objectives, behavioural rules, and learning mechanisms. Simulating stakeholder interactions enables researchers to explore emergent system-level dynamics arising from coordinated or uncoordinated decision processes, providing insights into how technology adoption, regulatory changes, and market shifts influence sustainable oil recovery outcomes.

2. Methodology

This study employs agent-based frameworks to represent complex socio-technical interactions in sustainable oil recovery operations. An agent-based framework established a platform for simulating heterogeneous actors and emergent system behaviours. It is also well-suited to this application because oil recovery decisions arise from decentralised interactions among technical experts, regulatory institutions, market agents, and geopolitical forces, each operating under bounded rationality and limited information.

The framework adheres to core agent-based principles: heterogeneity, bounded rationality, local interactions, emergent behaviour, and adaptive learning. Agents differ in their objectives, capabilities, and decision-making rules; they make decisions with incomplete information, interact with one another and their environment, and adjust their behaviour in response to feedback and outcomes (Bonabeau 2002).

The agent-based framework includes nine agent classes organized into three functional groups: technical, business, and regulatory/market stakeholders. Technical agents represent petrophysicists, drilling engineers, geologists, and reservoir engineers who prioritize operational integrity, data accuracy, and technical performance. Business agents include oil operators and service companies focusing on economic performance, investment efficiency, and strategic planning (Frooman 1999). Regulatory and market agents encompass government regulators, oil market participants, and geopolitical actors who shape the external conditions under which operations occur.

UDAR technology is modelled as a high-resolution information subsystem that delivers multidimensional insights into resistivity beyond the immediate wellbore (Manuaba et al., 2025a). Its capabilities include 3D far-field characterisation, azimuthal sensitivity, real-time data updates, and support for identifying bypassed zones and optimising EOR strategies. By embedding UDAR as a central information node, the model captures how advanced subsurface imaging improves decision-making across technical, business, and regulatory domains (Manuaba et al., 2024).

Table 1.
Types of agents

Agent	Type of agent
Petrophysicists	Technical Agent
Drilling Engineers	Technical Agent
Geologists	Technical Agent
Reservoir Engineers	Technical Agent
Oil Operator/Asset Manager	Business Agent
Service Companies	Business Agent & Technical Agent
Government/Regulators	Regulatory & Market Agent
Oil World Market	Regulatory & Market Agent
Geopolitics/Externalities	Regulatory & Market Agent

The model incorporates a multidimensional decision framework grounded in four key criteria that influence all agent classes: economic feasibility, environmental impact, technical risk, and political stability. Economic feasibility is assessed using net present value (NPV) and return on investment (ROI) metrics. Environmental impact encompasses emissions, water usage, and energy efficiency. Technical risk arises from uncertainties in geology, drilling, and tool performance. Political stability captures regulatory consistency, geopolitical risk, and long-term investment security (Agle et al., 1999).

Multiple iterations of a feasibility study are conducted on the UDAR-based BHA prior to the start of the development campaign (Figure 2). Beyond this, a more extensive simulation is done for the different dimensions mentioned in the frame. For example, different scenarios are simulated to evaluate and quantify technology adoption, such as including the elimination of pilot holes, sidetrack avoidance, and drilling performance improvements enabled by UDAR technology.

Validation followed a multi-step approach involving face validity, empirical comparison, and sensitivity analysis (Macal & North 2010). Subject-matter experts reviewed the model structure and agent rules, historical behaviour, and published industry data to benchmark outputs. Key parameters were systematically varied to assess robustness and internal consistency.

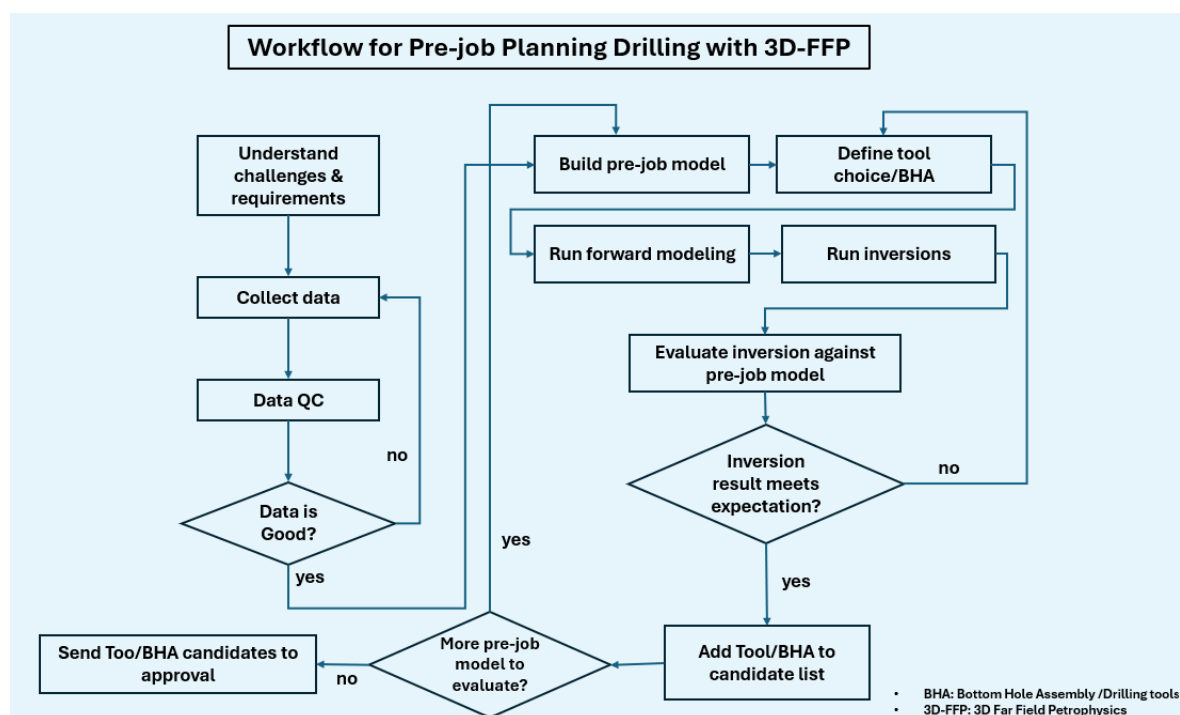


Figure 2.

Flowchart of the UDAR pre-job planning workflow, showing the iterative feasibility-study loop applied to the UDAR-based BHA design prior to the start of the drilling campaign.

3.1 Agent Architecture and Interactions

This section outlines the behavioural rules, interaction mechanisms, and feedback structures that govern agent dynamics in the proposed model. Together, these components shape emergent outcomes of sustainable oil recovery operations. Each agent type operates according to distinct behavioural rules that reflect professional, organisational, and external constraints observed in real-world oil recovery environments. Technical agents prioritise data quality, risk management, performance optimisation, and collaborative information sharing. Business agents focus on profit maximization, risk balancing, market positioning, and stakeholder management. Regulatory agents emphasize compliance monitoring, policy development, and international coordination where applicable (Clarkson 1995).

Agent interactions occur through structured communication channels, negotiation processes, and collaborative decision mechanisms. Information exchange forms the backbone of communication, with UDAR playing a central role by providing real-time resistivity measurements and multidimensional subsurface visualization (Manuaba et al., 2025a; Pewekar et al., 2025). Negotiation protocols arise when agents' objectives conflict or require alignment, for example, in budget allocation, regulatory approvals, or service contracting. Collaborative decision-making occurs through multidisciplinary project teams, technical committees, and regulatory consultations.

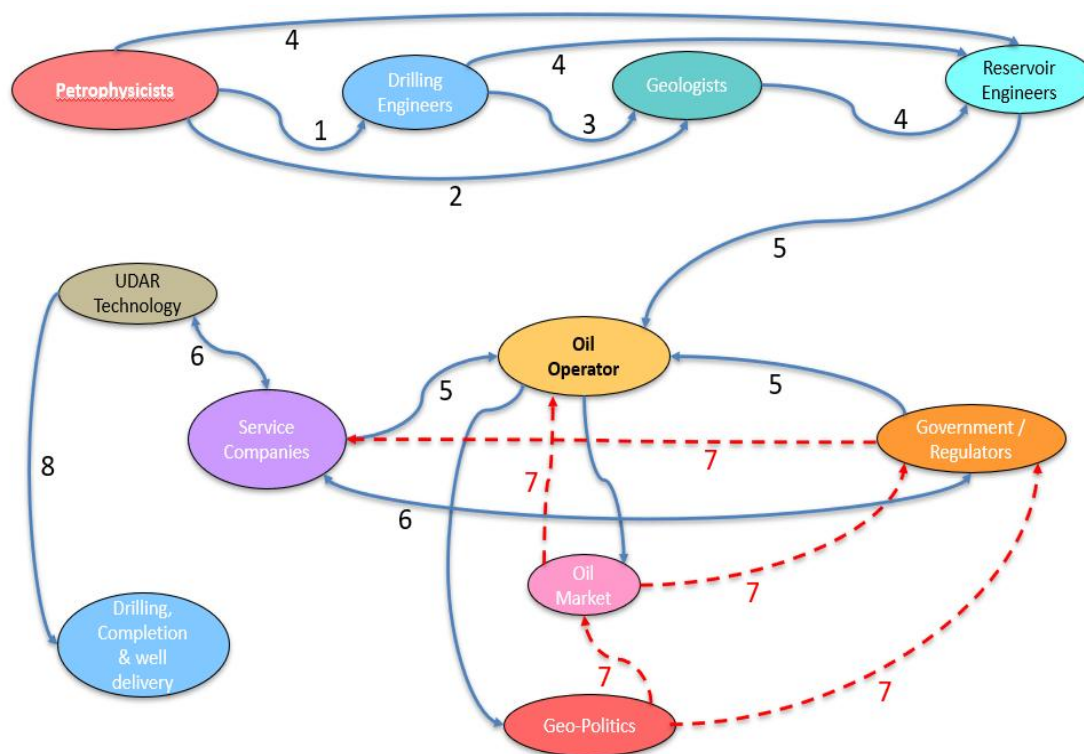


Figure 3.

Schematic of agent interactions within the multi-stakeholder framework, showing information flows and feedback loops among technical, business, and regulatory/market agents. Numbered links correspond to the interaction descriptions in Table 2.

Feedback loops are embedded in three primary mechanisms. The market feedback loop captures how oil prices, shifts in demand, and geopolitical events influence production strategies and technology adoption. The regulatory alignment loop represents an iterative interaction among operators, service companies, and regulators as standards evolve in tandem with technological capabilities. The technology integration loop captures how UDAR performance influences its adoption, with learning effects and innovation feedback reinforcing its strategic value over time.

3.2 Decision rules, parameter sources, and simulation settings

Decision rules. Each agent class follows condition-action rules operating on a shared set of state variables (UDAR data confidence, water-cut trend, oil price, and a regulatory-stringency index). Representative rules include: (i) petrophysicists and geologists trigger re-evaluation of the geo-steering plan when the UDAR-derived stand-off from the gas-oil or water-oil contact falls below a minimum threshold, consistent with the ~30 ft stand-off applied on well XYZ-02; (ii) drilling engineers select the BHA configuration (LWD-only vs. LWD+UDAR) by comparing incremental service cost against the expected reduction in pilot-hole/sidetrack probability; (iii) the oil operator approves continued UDAR deployment when projected incremental NPV exceeds a minimum hurdle rate, consistent with the 10% discount rate in Table 7; (iv) government/regulator agents revise compliance requirements when observed environmental or safety indicators cross the low/medium/high stringency thresholds summarized in Table 4; and (v) oil-market and geopolitical agents update price and risk signals each period from the same Brent price series used in the well economic evaluation (Table 7), which propagates to operator and service-company decisions.

Parameter sources. Parameters were drawn from three sources: (1) published industry and academic literature on UDAR performance, agent-based methodology, and sustainability metrics, cited throughout the Literature Review and Materials and Methods sections; (2) project/field data for the three example wells, including the drilling and completion cost breakdowns (Tables 8, 11, 14), production and water-cut histories (Tables 9-10, 12-13, 15-16), and the fiscal and operating assumptions in Table 7; and (3) structured consultation with subject-matter experts in petrophysics, drilling engineering, and reservoir/economic evaluation, who reviewed the agent behavioral rules and parameter ranges for realism.

Simulation settings. The model was implemented using a discrete time step matching the quarterly reporting interval used in the well economic assessment (Tables 9-10, 12-13, 15-16). Each scenario (Example #1 - Conventional Approach; Example #2 - UDAR-Enabled Approach; and the three sensitivity scenarios in Table 4) was run to characterize variability in oil price and water-cut trajectories, with results reported as most likely case values.

Validation and sensitivity analysis. Model validation combined three complementary checks, following Macal & North (2010): (1) face validity, in which subject-matter experts reviewed agent structures, interaction rules, and simulated outputs against professional experience; (2) empirical comparison, in which simulated technology-adoption paths, cost trajectories, and water-cut development were benchmarked against the historical field data for wells XYZ-01, XYZ-02, and XYZ-03 (Tables 6-16); and (3) one-at-a-time sensitivity analysis, in which UDAR service cost, regulatory stringency, and oil-price volatility were varied to test the robustness of the adoption and economic outcomes summarized in Table 4.

Table 2.
Agent interactions

Agent/s	To agent	Interactions	Feedback loop
Petrophysicists ⁽¹⁾	Drilling Engineers	1. Share well logs and formation evaluation data 2. Collaborate on real-time drilling decisions 3. Provide mutual feedback on geological interpretations.	NA
Petrophysicists ⁽²⁾	Geologists	1. Exchange rock properties and porosity analysis 2. Integrate structural and stratigraphic information 3. Validate geological models with petrophysical data	NA
Drilling Engineers ⁽³⁾	Geologists	1. Incorporate geological constraints into drilling plans 2. Share structural data and formation boundaries 3. Coordinate on optimal well trajectories	NA
Petrophysicists, Drilling Engineers, Geologists ⁽⁴⁾	Reservoir engineers	1. Provide integrated data for reservoir modelling 2. Collaborate on production optimization strategies 3. Share insights on field development planning	NA
Reservoir Engineers, Service Companies, Government/Regulators ⁽⁵⁾	Oil operator / asset manager	1. Receive production forecasts and recovery strategies from reservoir engineers 2. Contract services and technologies from service companies 3. Ensure regulatory compliance through government interactions 4. Respond to market signals and geopolitical influences	NA
UDAR Technology, Government/Regulators ⁽⁶⁾	Service companies	1. Deploy and maintain UDAR technology systems 2. Offer specialized expertise in enhanced recovery methods 3. Support regulatory compliance through environmental services	NA
Government / Regulators ⁽⁷⁾	Government / regulators	1. Establish policy frameworks that influence market operations 2. Set environmental standards and safety requirements 3. Issue permits and monitor compliance 4. Coordinate with international bodies on global standards	1. Service companies and government/regulators maintain ongoing dialogue 2. Technology deployment adapts to evolving regulatory requirements 3. Compliance strategies evolve with changing environmental standards
Oil World Market ⁽⁷⁾	Oil world market	1. Responds to regulatory changes and policy frameworks 2. Influences investment decisions through price signals 3. Reflects supply-demand dynamics and economic conditions	1. Oil operators receive market signals that influence operational decisions 2. Production strategies adapt to price volatility and demand changes 3. Investment priorities shift based on economic indicators
Geopolitics / Externalities ⁽⁷⁾	Geopolitics / externalities	1. Affects market access and operational permissions 2. Influences regulatory frameworks through international relations 3. Creates risks and opportunities through sanctions and agreements	NA

3. Result and discussion

3.3 Agent-based framework

The agent-based framework was implemented to simulate the dynamics of a representative oil field development project. Implementation integrates heterogeneous stakeholders, operational constraints, and technological inputs from UDAR measurements (Manuaba et al., 2025a). Parameter values were selected through review of published industry literature and consultation with domain experts to ensure realistic field conditions.

The model includes nine agent categories, with population sizes that reflect typical organizational structures in oil field operations. Key variable parameters include the adoption rate of UDAR technology, environmental regulation stringency, and oil price volatility.

Table 3
Number of Agents

Agent	Number of agents
Petrophysicists	5
Drilling Engineers	8
Geologists	6
Reservoir Engineers	4
Oil Operator / Asset Manager	1
Service Companies	1
Government / Regulators	1
Oil World Market	1
Geopolitics / Externalities	1

Two core example scenarios were evaluated with the parameters below, Key simulation parameters include:

- UDAR technology adoption rate: none to 100% adoption
- Environmental regulation stringency: Variable (low/medium/high)
- Oil price volatility: Brent published price

Example#1: Conventional Approach, Agents involved

- Drilling Engineer
- Oil Operator
- Government/Regulator
- Oil market
- Geopolitics

Standard drilling equipment, In the conventional approach, standard drilling equipment is used without UDAR integration (Manuaba et al., 2024). Results show longer drilling time, greater uncertainty in identifying high-value zones, and moderate project economics.

Example#2 UDAR-Enabled Approach, Agents involved

- Petrophysicists
- Geologists
- Drilling Engineers
- Reservoir Engineers
- Oil Operator
- Service Company
- Government/Regulator
- Oil market
- Geopolitics

UDAR adoption rate 100% for drilling equipment. In the UDAR-enabled approach, a broader set of stakeholders is engaged with moderate UDAR adoption. Results indicate improved reservoir characterization, enhanced geosteering accuracy, higher recovery factors, and greater economic viability despite higher upfront drilling costs.

Baseline scenario comparisons demonstrate clear performance improvements across economic, environmental, and stakeholder dimensions. Economic performance improves through increased net present value and higher recovery factors, with incremental drilling costs more than offset by improved production outcomes. Environmental performance is expected to benefit from more precise well placement, reducing unnecessary drilling intervals, though quantification of environmental metrics was beyond the scope of this study. Stakeholder alignment is most evident among technical and regulatory agents in the UDAR scenario, driven by improved subsurface data quality and clearer compliance pathways (Clarkson 1995; Manuaba et al., 2024).

Scenario analysis further explores outcomes under accelerated UDAR adoption, more stringent environmental regulations, and heightened market volatility (Ringle et al., 2016). Higher UDAR adoption amplifies both economic and sustainability benefits. Strict environmental regulations incentivize faster technology deployment and closer collaboration between technical and regulatory agents. Under volatile market conditions, UDAR's risk reduction capabilities and real-time decision support become particularly valuable.

Table 4.
Scenario analysis

Scenario analysis	
Accelerated UDAR adoption	Substantial improvement in field development economics
	Significant reduction in environmental impact
	Enhanced stakeholder collaboration and satisfaction
	Accelerated technology adoption
Stringent environmental regulations	Increased focus on sustainability metrics
	Enhanced collaboration between technical and regulatory agents
	Increased emphasis on operational flexibility
Market Volatility	Greater value is placed on the risk-reduction benefits of UDAR technology.
	Enhanced importance of real-time decision-making capabilities

Note: environmental and stakeholder-collaboration outcomes in this table represent modelled/expected effects of the scenarios described; direct measurement of emissions or resource-use reduction was outside the scope of this study.

Sensitivity analysis highlights the influence of UDAR technology costs, regulatory stringency, and market conditions on adoption dynamics and sustainability outcomes. Cost reductions and subsidies accelerate deployment; moderate-to-stringent regulations increase technology uptake; and market conditions shape the strategic value of flexible, knowledge-intensive technologies like UDAR. Model validation against historical patterns and expert expectations indicates the framework captures realistic adoption behaviour, economic performance trends, and environmental improvement trajectories.

The framework validation confirms its empirical and practical credibility through a two-pronged approach. Historically, the simulation demonstrates strong alignment with real-world data, as evidenced by technology adoption patterns that match observed industry behaviour, economic performance metrics that align with published field studies, and environmental improvement rates that are consistent with established industry reports. This empirical grounding is further substantiated by a formal industry expert review, which verified that the model's agent behaviours authentically reflect real-world decision-making processes, its interaction mechanisms accurately represent common industry practices, and its final outputs consistently align with expert expectations and professional experience (Ganguli & Dimri 2023; Manuaba et al., 2025a).

3.4 Well economic

An agent-based framework was used in the two scenarios above to reflect the results of decision-making in drilling, with or without UDAR technology. Three wells were analysed in the same field, but drilled by different service companies. These wells represent examples of UDAR utilization ranging from 0% to 33% and 100%. Table 5 below indicates the similarity of the objective, the target reservoir, and the length of the horizontal section. While the three wells share the same target reservoir interval and planned horizontal length, the differences in water-cut development and production performance discussed below cannot be attributed to UDAR utilization alone: local geological heterogeneity, completion design (e.g., the placement of packers/barriers described in the Identifying Water Corridors and Completion Design subsection and Figure 7), and operating conditions such as choke management can also influence these outcomes. The three-well comparison is therefore best interpreted as an illustrative field validation rather than a controlled experiment isolating the effect of UDAR.

Table 5
Comparative summary of the three well examples

Parameter	XYZ-01 (LWD only)	XYZ-02 (30% UDAR)	XYZ-03 (100% UDAR)
UDAR coverage of the horizontal section	0%	30%	100%
Drilling cost (USD)	\$2,961,300	\$3,206,300	\$3,721,300
Completion & wellhead cost (USD)	\$7,600,000	\$7,600,000	\$7,600,000
Total D&C cost (USD)	\$10,561,300	\$10,806,300	\$11,321,300
Cumulative oil produced (bbl)	~1,008,100	~690,600	~1,908,900 (ongoing)
Water cut: start → end/current	5% → 55%	5% → 65%	5% → 6% (stabilized)
Producing period/status	~1.5 yr; shut-in on high water cut	~1 yr; shut-in on high water cut	>2 yr and ongoing; still producing
Cumulative NPV (USD)*	\$55,134,731	\$28,698,509	\$78,408,229 (still accruing)

* Cumulative NPV values are the last reported period-end figures from Tables 9, 12, and 15, respectively; the XYZ-03 value is still accruing because the well remains in production.

Table 6.
List of well examples

No	Well	Objective	Target reservoir	Target production rate bbl/d	Target water-cut	Year start	Year end	Water-cut year end	Misc
1	XYZ-01	Single lateral oil producer	3,500 ft lateral in Layer-1	3,000	<5%	01-Jan-22	30-Jun-23	55%	Shutdown
2	XYZ-02	Single lateral oil producer	3,500 ft lateral in Layer-1	3,000	<5%	01-Jul-23	30-Jun-24	65%	Shutdown
3	XYZ-03	Single lateral oil producer	3,500 ft lateral in Layer-1	3,000	<5%	01-Jan-24	on going	6%	Production

The reservoir was heterogeneous with 3-phase fluid content, gas, oil and water, with oil thickness about 30 to 50 ft TVD. The well aims to drill below the gas-oil contact and above the oil-water contact, away from water but not too close to the gas cap.

Based on agreement among agents, petrophysicists, geologists, drilling engineers, reservoir engineers, and the oil operator, and on the service company's execution of drilling well placement, the well was drilled with only an LWD sensor. A few reasons drive this decision, such as cost savings, a high degree of confidence (initially) in the capability of mapping the fluid contact (GOC & WOC), and a shorter BHA (Bottom Hole Assembly) to reduce the risk of a stuck that can lead to loss of the well, detailed below for drilling and completion. Drilling cost is highlighted in light pink in Table 8.

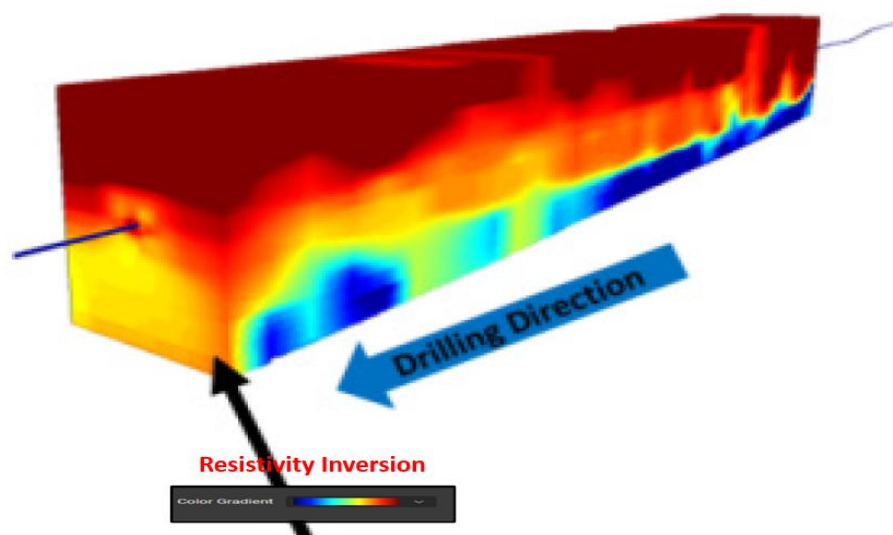


Figure 4.

UDAR-derived 3-phase fluid mapping showing the spatial distribution of gas, oil, and water around the wellbore, used to guide well placement between the gas-oil and oil-water contacts.

Table 7.
Well basic parameters

Parameter	Value
Initial total liquid rate Q-liquid (bbl./d)	3,000
Decline model	Exponential
Annual exponential decline rate	20.00%
Initial water cut (fraction)	5.00%
Completion cost per well (incl. tree/wellhead) (USD)	\$7,600,000.00
Royalty rate	12.50%
Tax rate (applied to positive operating net)	5.00%
Lifting cost (USD per bbl. of oil)	\$11.00
Discount rate (annual)	10.00%
Oil price source	Quarterly average of the monthly Brent crude oil

Example 1: Well XYZ-01 (Near Field Petrophysics utilising LWD only) Based on agreement among agents, petrophysicists, geologists, drilling engineers, reservoir engineers, and the oil operator, and on the service company's execution of drilling well placement, the well was drilled with only an LWD sensor. A few reasons drive this decision, such as cost savings, a high degree of confidence (initially) in the capability of mapping the fluid contact (GOC & WOC), and a shorter BHA (Bottom Hole Assembly) to reduce the risk of a stuck that can lead to loss of the well, detailed below for drilling and completion. Drilling cost is highlighted in light pink in Table 8.

Table 8.
XYZ-01 drilling & completion cost

No	Service (LWD and 0% UDAR Utilisation)	Cost
1	Directional Drilling & Logging While Drilling (MWD, LWD, RSS, DD & MWD Engineer, Non-Drilling Hour-LWD)	\$511,300.0
2	Advanced Geo-Steering & UDAR (UDAR, Geo-Steering Engineer, Non-Drilling Hour-UDAR)	\$0.0
3	Rig rental	\$2,450,000.0
	<i>Drilling Cost</i>	<i>\$2,961,300.0</i>
4	Completion & wellhead	\$7,600,000.0
	Total Cost	\$10,561,300.0

Given the target liquid production rate of about 3,000 bbl/d and the other parameters listed in Table 6, which were controlled by a surface production choke valve, revenue and other quantities were calculated. During the production period from January 2022 to mid-2023, the well reached a water cut of up to 55%, while initial production was only 5%. In that state, the well was shut down due to limitations on surface water treatment facilities. Tables 9 & 10, below, as a result of that period production, such as net cash flow, PV of net cash flow and cumulative NPV.

Table 9.
XYZ-01 Economic assessment

Period Start	Period End	Days	WC Start	WC End	WC Avg	Liquid Rate @ Mid (bbl/d)	Oil Rate Avg (bopd)	Oil Produced (bbl)	Avg Brent Price (USD/bbl)	Gross Revenue (USD)
2022-01-01	2022-03-31	90	5.00%	13.17%	9.08%	2,926.93	2,661.09	239,498.22	\$97.44	\$23,337,455.44
2022-04-01	2022-06-30	91	13.26%	21.51%	17.39%	2,786.09	2,301.72	209,456.56	\$111.99	\$23,456,487.39
2022-07-01	2022-09-30	92	21.61%	29.95%	25.78%	2,649.12	1,966.18	180,888.94	\$97.83	\$17,697,214.02
2022-10-01	2022-12-31	92	30.05%	38.39%	34.22%	2,518.89	1,656.92	152,436.67	\$88.72	\$13,524,200.88
2023-01-01	2023-03-31	90	38.49%	46.65%	42.57%	2,396.37	1,376.26	123,863.71	\$82.32	\$10,196,907.88
2023-04-01	2023-06-30	91	46.74%	55.00%	50.87%	2,281.06	1,120.65	101,979.02	\$78.09	\$7,963,147.07

Table 10.
XYZ-01 Economic assessment (continued)

Period Start	Period End	Royalty (USD)	Lifting Cost (USD)	Operating Net Before Tax (USD)	Tax (USD)	Net CF Before Capex (USD)	Capex (Drilling+Completion) (USD)	Net CF After Capex (USD)	PV of Net CF (USD)	Cumulative NPV (USD)
2022-01-01	2022-03-31	\$2,917,181.93	\$2,634,480.42	\$17,785,793.10	\$889,289.65	\$16,896,503.44	\$10,561,300.00	\$6,335,203.44	\$6,137,821.84	\$6,137,821.84
2022-04-01	2022-06-30	\$2,932,060.92	\$2,304,022.19	\$18,220,404.27	\$911,020.21	\$17,309,384.06	\$0.00	\$17,309,384.06	\$16,709,828.43	\$22,847,650.27
2022-07-01	2022-09-30	\$2,212,151.75	\$1,989,778.33	\$13,495,283.94	\$674,764.20	\$12,820,519.74	\$0.00	\$12,820,519.74	\$12,082,666.37	\$34,930,316.64
2022-10-01	2022-12-31	\$1,690,525.11	\$1,676,803.34	\$10,156,872.44	\$507,843.62	\$9,649,028.81	\$0.00	\$9,649,028.81	\$8,877,844.43	\$43,808,161.07
2023-01-01	2023-03-31	\$1,274,613.49	\$1,362,500.77	\$7,559,793.63	\$377,989.68	\$7,181,803.94	\$0.00	\$7,181,803.94	\$6,452,643.21	\$50,260,804.28
2023-04-01	2023-06-30	\$995,393.38	\$1,121,769.22	\$5,845,984.46	\$292,299.22	\$5,553,685.24	\$0.00	\$5,553,685.24	\$4,873,926.25	\$55,134,730.53

Example 2: Well XYZ-02 (Near Field Petrophysics & 30% Far Field Petrophysics). Unlike well XYZ-01, well XYZ-02 was initially drilled with LWD & UDAR technology; after reaching 30% of the total horizontal length, it was converted to LWD-only and continued drilling to total depth. Longer LWD tools, consequently with longer BHA, re-modelling for drilling technical with acceptable and doable results in Figure 5. 30% of the planned horizontal section to map the fluid between gas, oil and water. Based on that, the well will be placed around 5-10 ft below the gas and with a minimum stand-off of around 30 ft above the water contact. Below is Table 11, a breakdown cost estimate for drilling.

Table 11.
XYZ-02 drilling & completion cost

No	Service (LWD and 30% UDAR Utilisation)	Cost
1	Directional Drilling & Logging While Drilling (MWD, LWD, RSS, DD & MWD Engineer, Non-Drilling Hour-1)	\$431,300.0
2	Advanced Geo-Steering & UDAR (UDAR, Geo-Steering Engineer, Non-Drilling Hour-2)	\$325,000.0
3	Rig rental	\$2,450,000.0
	Drilling Cost	\$3,206,300.0
4	Completion & wellhead	\$7,600,000.0
	Total Cost	\$10,806,300.0

About \$245,000 in increased drilling costs compared with the previous well, XYZ-01. Well XYZ-02 started production in the middle of 2023 and fell off in less than 1 year to a 65% water cut. The well was shut down due to high water cut by the end of June 2024. This is a significant impact of oil production in that particular XYZ field, as shown in [Tables 12 and 13](#).

Table 12.
XYZ-02 economic assessment

Period Start	Period End	Days	WC Start	WC End	WC Avg	Declined Qliq @ Mid (bbl/d)	Oil Rate Avg (bopd)	Oil Produced (bbl)	Avg Brent Price (USD/bbl)	Gross Revenue (USD)
2023-07-01	2023-09-30	92	5.00%	19.96%	12.48%	3,079.29	2,695.01	247,941.32	\$85.98	\$21,318,873.97
2023-10-01	2023-12-31	92	20.12%	35.08%	27.60%	2,927.91	2,119.73	195,014.91	\$82.89	\$16,165,113.34
2024-01-01	2024-03-31	91	35.25%	50.04%	42.64%	2,785.50	1,597.65	145,386.51	\$81.96	\$11,915,255.20
2024-04-01	2024-06-30	91	50.21%	65.00%	57.60%	2,650.01	1,123.53	102,241.35	\$84.98	\$8,688,672.88

Table 13.
XYZ-02 economic assessment (continued)

Period Start	Period End	Days	WC Start	WC End	WC Avg	Declined Qliq @ Mid (bbl/d)	Oil Rate Avg (bopd)	Oil Produced (bbl)	Avg Brent Price (USD/bbl)	Gross Revenue (USD)
2023-07-01	2023-09-30	92	5.00%	19.96%	12.48%	3,079.29	2,695.01	247,941.32	\$85.98	\$21,318,873.97
2023-10-01	2023-12-31	92	20.12%	35.08%	27.60%	2,927.91	2,119.73	195,014.91	\$82.89	\$16,165,113.34
2024-01-01	2024-03-31	91	35.25%	50.04%	42.64%	2,785.50	1,597.65	145,386.51	\$81.96	\$11,915,255.20
2024-04-01	2024-06-30	91	50.21%	65.00%	57.60%	2,650.01	1,123.53	102,241.35	\$84.98	\$8,688,672.88

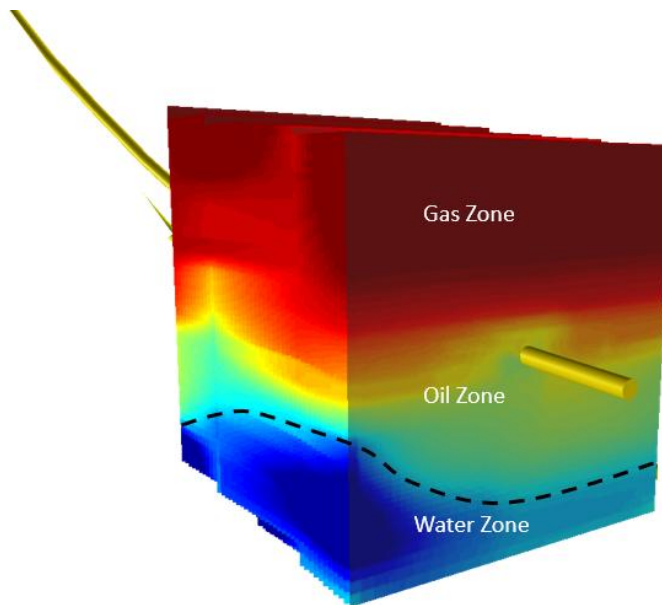


Figure 5.
UDAR-derived 3-phase fluid mapping for well XYZ-02, showing the gas, oil, and water distribution along the 30% of the horizontal section drilled with UDAR technology.

Example 3: Well, XYZ-03 (3D-Far Field Petrophysics Adoption). When Well XYZ-02 indicated that oil production would decline as water cut increased, all agents sat together and analyzed the room for opportunities to improve. It concluded that drilling the entire horizontal section with LWD and UDAR technology. The extra cost comparison between the first and second wells is \$760,000 and \$515,000, respectively. As listed below for drilling and completion cost in [Table 14](#).

Table 14.
XYZ-03 drilling & completion cost

No	Service (LWD and 100% UDAR Utilisation)	Cost
1	Directional Drilling & Logging While Drilling (MWD, LWD, RSS, DD & MWD Engineer)	\$391,300.0
2	Advanced Geo-Steering & UDAR (UDAR, Geo-Steering Engineer, Non-Drilling Hour)	\$880,000.0
3	Rig rental	\$2,450,000.0
	Drilling Cost	\$3,721,300.0
4	Completion & wellhead	\$7,600,000.0
	Total Cost	\$11,321,300.0

Table 15
XYZ-03 economic assessment

Period Start	Period End	Days	WC Start	WC End	WC Avg	Declined Qliq @ Mid (bbl/d)	Oil Rate Avg (bopd)	Oil Produced (bbl)	Avg Brent Price (USD/bbl)	Gross Revenue (USD)
2024-01-01	2024-03-31	91	5.00%	5.25%	5.12%	3,080.98	2,923.13	266,005.15	\$81.96	\$21,800,641.72
2024-04-01	2024-06-30	91	5.25%	5.50%	5.37%	2,931.12	2,773.64	252,401.58	\$84.98	\$21,449,587.81
2024-07-01	2024-09-30	92	5.50%	5.75%	5.62%	2,787.02	2,630.30	241,987.68	\$78.71	\$19,046,443.09
2024-10-01	2024-12-31	92	5.75%	6.00%	5.88%	2,650.01	2,494.31	229,476.71	\$74.00	\$16,981,492.51
2025-01-01	2025-03-31	90	6.00%	6.00%	6.00%	2,521.11	2,369.85	213,286.08	\$75.04	\$16,005,580.61
2025-04-01	2025-06-30	91	6.00%	6.00%	6.00%	2,399.80	2,255.81	205,278.82	\$66.96	\$13,744,557.23
2025-07-01	2025-09-30	92	6.00%	6.00%	6.00%	2,281.82	2,144.91	197,331.93	\$68.14	\$13,446,076.83
2025-10-01	2025-12-31	92	6.00%	6.00%	6.00%	2,169.64	2,039.47	187,630.82	\$63.16	\$11,851,119.72
2026-01-01	2026-02-28	59	6.00%	6.00%	6.00%	2,082.29	1,957.35	115,483.69	\$64.59	\$7,459,563.67

Table 16.
XYZ-03 economic assessment (continued)

Period Start	Period End	Royalty (USD)	Lifting Cost (USD)	Operating Net Before Tax (USD)	Tax (USD)	Net CF Before Capex (USD)	Capex (Drilling+Completion) (USD)	Net CF After Capex (USD)	PV of Net CF (USD)	Cumulative NPV (USD)
2024-01-01	2024-03-31	\$2,725,080.21	\$2,926,056.60	\$16,149,504.90	\$807,475.24	\$15,342,029.65	\$11,321,300.00	\$4,020,729.65	\$3,841,507.10	\$3,841,507.10
2024-04-01	2024-06-30	\$2,681,198.48	\$2,776,417.41	\$15,991,971.93	\$799,598.60	\$15,192,373.33	\$0.00	\$15,192,373.33	\$14,662,316.71	\$18,503,823.81
2024-07-01	2024-09-30	\$2,380,805.39	\$2,661,864.49	\$14,003,773.21	\$700,188.66	\$13,303,584.55	\$0.00	\$13,303,584.55	\$12,534,656.05	\$31,038,479.86
2024-10-01	2024-12-31	\$2,122,686.56	\$2,524,243.84	\$12,334,562.10	\$616,728.10	\$11,717,833.99	\$0.00	\$11,717,833.99	\$10,778,488.52	\$41,816,968.39
2025-01-01	2025-03-31	\$2,000,697.58	\$2,346,146.90	\$11,658,736.13	\$582,936.81	\$11,075,799.33	\$0.00	\$11,075,799.33	\$9,948,687.31	\$51,765,655.70
2025-04-01	2025-06-30	\$1,718,069.65	\$2,258,066.99	\$9,768,420.59	\$488,421.03	\$9,279,999.56	\$0.00	\$9,279,999.56	\$8,142,021.46	\$59,907,677.16
2025-07-01	2025-09-30	\$1,680,759.60	\$2,170,651.26	\$9,594,665.96	\$479,733.30	\$9,114,932.66	\$0.00	\$9,114,932.66	\$7,807,365.78	\$67,715,042.94
2025-10-01	2025-12-31	\$1,481,389.96	\$2,063,938.98	\$8,305,790.77	\$415,289.54	\$7,890,501.23	\$0.00	\$7,890,501.23	\$6,598,153.72	\$74,313,196.66
2026-01-01	2026-02-28	\$932,445.46	\$1,270,320.54	\$5,256,797.67	\$262,839.88	\$4,993,957.79	\$0.00	\$4,993,957.79	\$4,095,032.55	\$78,408,229.21

As illustrated in Figure 6, the adoption of UDAR technology can deliver a well with a zone of interest that yields a net-to-gross (NTG) ratio of up to 100%. Prolong well life with desired fluid production while increasing the efficiency and lifespan of surface facilities, such as water-oil, gas-oil separation.

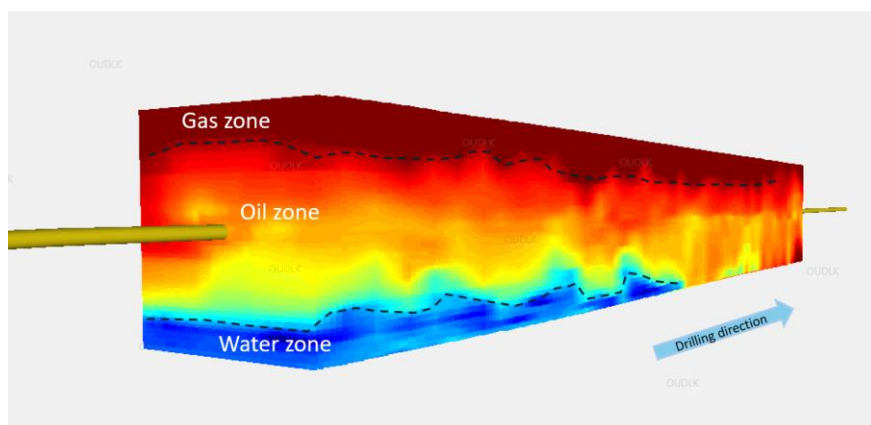


Figure 6.

UDAR-derived 3-phase fluid mapping for well XYZ-03, showing the gas, oil, and water distribution across the full (100%) length of the horizontal section drilled with UDAR technology, corresponding to the high net-to-gross ratio discussed in the text. Adapted from Manuaba et al. (2025b).

3.5 Identifying Water Corridors and Completion Design

Another advantage of UDAR technology is optimising production and reducing water production delays by detecting potential water corridors that contribute to water flow toward the wellbore trajectory. This can be achieved through a combination of in-depth investigation of UDAR and microimaging from other services. By incorporating 360-degree (azimuthal) perspectives, these advanced techniques provide a significantly improved understanding of fluid behaviour within reservoir layers, supporting more informed management decisions (Manuaba et al., 2023).

Knowing the potential water path, production can be optimized by setting packers/barriers in the right section to delay water flow and allow only hydrocarbon flow into the wellbore. The illustration in Figure 7 below was proposed for one of the wells, which used UDAR technology along with a micro-resistivity image to identify fractures. The completion design is optimized across different zones of the rock structure, which can help prevent early water breakthroughs and improve overall sweep efficiency (Manuaba et al., 2023).

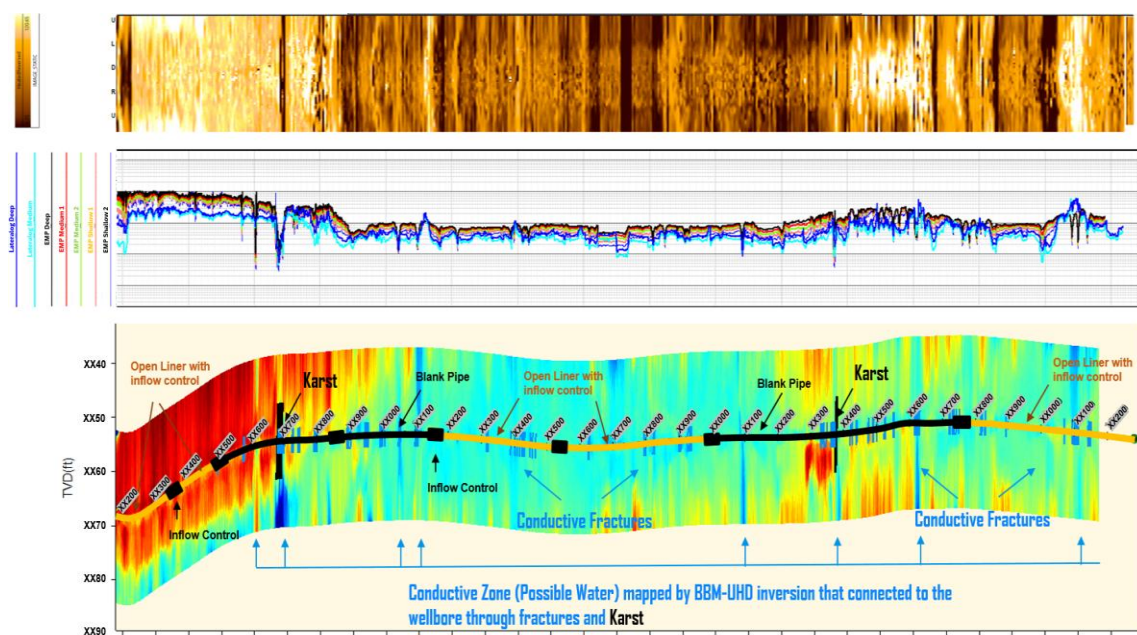


Figure 7.

Completion design illustrating how a UDAR-identified water corridor is sealed with blank pipe sections to delay water breakthrough and preserve hydrocarbon inflow into the wellbore. Adapted from Manuaba et al. (2023).

4. Result and discussion

Results highlight the substantial potential of integrating an agent-based framework with Ultra-Deep Azimuthal Resistivity (UDAR) technology to support sustainable oil recovery. The combined framework enables systematic assessment of how technological innovation, stakeholder behaviour, and regulatory structures co-evolve to influence operational and sustainability outcomes. The model captures the complex interplay between technology, stakeholder coordination, regulatory drivers, and market forces (Agle et al., 1999).

Results demonstrate UDAR technology can yield significant improvements across multiple sustainability dimensions, including economic performance, environmental responsibility, technical efficiency, and stakeholder alignment. Enhanced subsurface intelligence improves reservoir understanding, reduces drilling uncertainty, and optimises well placement. Environmental benefits are anticipated through more precise well placement and reduced remedial operations, though direct measurement of emission and resource-use reductions was outside the scope of this study. The agent-based framework underscores that these benefits are maximised when stakeholders share information and coordinate decisions across disciplinary and organisational boundaries.

The framework yields several policy-relevant insights (Clarkson 1995). Economic incentives, such as tax credits, investment subsidies, and accelerated depreciation, can encourage the adoption of sustainable technologies.

From an industry perspective, the agent-based and UDAR integration framework offers practical applications for strategic planning, operational optimization, and regulatory engagement. Operators can use the framework to explore long-term technology investment strategies and risk profiles. Technical teams benefit from integrated workflows that enhance real-time decision-making and continuous improvement. Regulators can employ the framework to test policy options before implementation and refine compliance mechanisms (Clarkson 1995).

Novelty relative to prior work. Prior agent-based studies in the energy sector have largely modelled market, policy, or supply-chain dynamics without an explicit link to subsurface data quality (e.g., Bonabeau 2002; Basu 2017; Ringler et al., 2016), while UDAR-focused studies have concentrated on measurement physics, inversion, and geo-steering performance without representing the surrounding stakeholder decision environment (Ameneiro et al., 2023; Wu et al., 2023; Albaqami et al., 2025). The present study addresses this gap by embedding UDAR as a shared information node within a nine-agent, three-domain (technical/business/regulatory-market) decision framework, and by field-validating that framework against economic and production data from three sequentially drilled wells with increasing UDAR utilization (0%, 30%, and 100%). To the authors' knowledge, this combination of an agent-based, multi-stakeholder decision model parameterised and validated using real drilling, completion, and cash-flow data, and tied to a specific formation-evaluation technology, has not been reported previously.

Despite its advantages, the framework has several limitations. Agent behaviours are necessarily simplified representations of complex human and organizational dynamics (Bonabeau 2002). The geographic and operational scope is restricted to a single representative field, and regulatory conditions are treated as static across simulation runs. UDAR capabilities are modelled as fixed, though real-world technologies evolve (Albaqami et al., 2025; Wu et al., 2023). Future research should incorporate dynamic regulation, evolving technology performance and costs, multi-field or regional simulations, and more sophisticated behavioural models that capture social influence, organizational learning, and bounded rationality in greater detail (Phillips et al., 2003; Ringler et al., 2016).

5. Conclusion

This study presents a comprehensive agent-based framework integrating Ultra-Deep Azimuthal Resistivity (UDAR) technology with multi-stakeholder decision-making to advance sustainable oil recovery (Bonabeau 2002; Macal & North 2010; Manuaba et al., 2025a). Results demonstrate considerable potential of combining high-resolution subsurface characterization with multi-agent coordination to achieve improved economic,

environmental, and operational performance. The model captures the complex interplay among technology, stakeholder behaviour, regulatory structures, and market forces, offering valuable insights into the mechanisms that enable sustainable field development (Freeman 1984; Ringler et al., 2016).

Key findings include UDAR technology's central role as an information hub (Manuaba et al., 2025a; Pewekar et al., 2025), the importance of stakeholder coordination in realizing sustainability benefits, and the feasibility of embedding environmental and social metrics into operational decision-making. Analysis shows that government policy frameworks, including economic incentives and performance standards, shape the conditions under which technology adoption and sustainability improvements occur. Feedback mechanisms in the model facilitate adaptive management, enabling agents to adjust their strategies based on observed system performance (Macal & North 2010).

The research has several practical implications. Oil operators can use the framework to inform strategic planning and technology investment decisions. Service companies can refine deployment and integration strategies. Regulators can evaluate potential impacts of policy interventions, and technology developers can align innovation with evolving industry and policy needs. In terms of contribution to knowledge, the study offers methodological innovation by developing an agent-based framework specifically tailored to the oil industry (Bonabeau 2002; Macal & North 2010), demonstrates a robust approach for integrating UDAR into multi-stakeholder decision environments (Manuaba et al., 2025a), and provides a structured way to incorporate sustainability considerations and policy analysis into operational modelling (Elkington 1997; Ringler et al., 2016).

Based on these insights, we recommend wider adoption of agent-based decision support systems in the oil sector (Macal & North 2010), targeted policy instruments to encourage sustainable technology deployment, international cooperation to harmonize environmental and operational standards (Bazilian et al., 2011), and continued research to extend the model to broader geographies, more dynamic regulatory environments, and more detailed behavioral representations (Phillips et al., 2003; Ringler et al., 2016).

6. Acknowledgement

The Authors would like to thank the Institut Teknologi Bandung at the School of Business and Management Department, Petroleum Engineering Department, for their support in finishing this manuscript.

7. Declarations

The authors declare that this manuscript reports original work that has not been published previously, is not under consideration for publication elsewhere, and has been read and approved by all authors and by the responsible institutions where the work was carried out.

6.1 Author contributions

I.B.G.H. Manuaba: Conceptualisation, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. D. Wibisono: Methodology, Validation, Review & Editing, Supervision. M.P.S. Siallagan: Investigation, Data Curation, Review & Editing. T. Marhaendrajana: Resources, Validation, Supervision. H. Wang: Software, Data Curation, Visualisation. All authors read and approved the final version of the manuscript.

6.2 Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The work was carried out as part of the authors' regular professional and academic duties at their respective institutions.

6.3 Competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

During the preparation of this manuscript, the authors used an AI-assisted tool (Claude, Anthropic) to support manuscript formatting to journal style, literature searching, and reference compilation. All AI-assisted output was reviewed, verified, and edited by the authors, who take full responsibility for the content, accuracy, and originality of the published work. No AI tool is listed as an author or credited with authorship.

8. Glossary of terms and symbols

Terms / symbols	Definition	Unit
UDAR	Ultra-deep azimuthal resistivity	—
LWD	Logging while drilling	—
MWD	Measurement while drilling	—
RSS	Rotary steerable system	—
DD	Directional driller	—
BHA	Bottom hole assembly	—
NPV	Net present value	USD
ROI	Return on Investment	%
NTG	Net-to-Gross ratio	fraction (v/v)
EOR	Enhanced oil recovery	—
WOC	Water–oil contact	ft (TVD)
GOC	Gas–oil contact	ft (TVD)
TVD	True vertical depth	ft
ESG	Environmental, Social, and Governance	—
AI	Artificial intelligence	—
SLB	Schlumberger Limited (oilfield services company)	—
SPE	Society of Petroleum Engineers	—
SPWLA	Society of Petrophysicists and Well Log Analysts	—
IPTC	International petroleum technology conference	—

9. References

- Agle, B. R., Mitchell, R. K., & Sonnenfeld, J. A. (1999). Who matters to CEOs? An investigation of stakeholder attributes and salience, corporate performance, and CEO values. *Academy of Management Journal*, 42(5), 507–525. <https://doi.org/10.5465/256973>
- Albaqami, N., Al-Ansari, Y., Alrowaili, S., et al. (2025). Increasing the resolution of the inversion by combining deep resistivity with ultra-deep resistivity. *SPE Middle East Oil & Gas Show and Conference*. <https://doi.org/10.2118/226907-MS>
- Ameneiro, R., Clegg, N., Walmsley, A., et al. (2023). 3-dimensional ultradeep azimuthal resistivity: A tool for identification of bypassed pay in mature fields. *SPWLA Annual Logging Symposium*. <https://doi.org/10.30632/spwla-2023-0071>
- Basu, S. (2017). Mobile app enabling instant, real-time integration of geology, petrophysics, reservoir engineering, production technology, petroleum engineering, production engineering, and process engineering disciplines (U.S. Patent Application).
- Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., & Yumkella, K. K. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, 39(12), 7896–7906. <https://doi.org/10.1016/j.enpol.2011.09.039>

- Bonabeau, E. (2002). Agent-based modelling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, 99(3), 7280–7287. <https://doi.org/10.1073/pnas.082080899>
- Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., & Mac Dowell, N. (2018). Carbon capture and storage (CCS): The way forward. *Energy & Environmental Science*, 11(5), 1062–1176. <https://doi.org/10.1039/C7EE02342A>
- Clarkson, M. E. (1995). A stakeholder framework for analyzing and evaluating corporate social performance. *Academy of Management Review*, 20(1), 92–117. <https://doi.org/10.5465/amr.1995.9503271994>
- Elkington, J. (1997). *Cannibals with forks: The triple bottom line of 21st century business*. Capstone Publishing.
- Erhueh, O. V., Esiri, A. E., & Wodu, E. K. (2023). Advancing petrophysical techniques for sustainable hydrocarbon extraction: Enhancing resource efficiency and minimizing waste. *World Journal of Advanced Research and Reviews*, 17(2), 243–258. <https://doi.org/10.30574/wjarr.2023.17.2.0243>
- Freeman, R. E. (1984). *Strategic management: A stakeholder approach*. Cambridge University Press.
- Frooman, J. (1999). Stakeholder influence strategies. *Academy of Management Review*, 24(2), 191–205. <https://doi.org/10.5465/amr.1999.1893939>
- Ganguli, S. S., & Dimri, V. P. (2023). Reservoir characterization: State-of-the-art, key challenges and ways forward. In *Developments in Structural Geology and Tectonics* (Vol. 8, pp. 389–427). Elsevier. <https://doi.org/10.1016/B978-0-323-99593-1.00015-X>
- Höök, M., & Tang, X. (2013). Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy*, 52, 797–809. <https://doi.org/10.1016/j.enpol.2012.10.046>
- Macal, C. M., & North, M. J. (2010). Tutorial on agent-based modelling and simulation. *Journal of Simulation*, 4(3), 151–162. <https://doi.org/10.1057/jos.2010.3>
- Manuaba, I. B. G. H., Aljishi, M. K., Santoso, G. I., & Dolan, J. T. (2023). Fracture network characterization beyond wellbores: A new approach to identify water corridors through advanced resistivity analysis (SPE-214995-MS). Society of Petroleum Engineers. <https://doi.org/10.2118/214995-MS>
- Manuaba, I. B. G. H., Ghanim, R. A., Bikchandaev, E., et al. (2024). Far-field petrophysics utilizing deep-resistivity high-definition and ultra-deep-resistivity 3D inversion in thin, laminated reservoirs. *International Petroleum Technology Conference*. <https://doi.org/10.2523/IPTC-23716-EA>
- Manuaba, I. B. G. H., Ghanim, R. A., Bikchandaev, E., et al. (2025a). Far field petrophysics for saturation mapping beyond the wellbore. *SPE Journal*. <https://doi.org/10.2118/231160-PA>
- Manuaba, I. B. G. H., Abdrabalnby, A. A., Wang, H., & Santoso, G. I. (2025b). Mapping water paths using ultra-high resolution borehole imaging and ultra-deep directional resistivity logging while drilling in carbonate reservoirs (SPE-226313-MS). <https://doi.org/10.2118/226313-MS>
- Pewekar, A., Abbas, Y., Ghosh, K., et al. (2025). Smart reservoir management and proactive model enhancement with ultra-deep azimuthal resistivity: From real-time mapping to post-drilling applications. *SPE Middle East Oil & Gas Show and Conference*. <https://doi.org/10.2118/226909-MS>
- Phillips, R., Freeman, R. E., & Wicks, A. C. (2003). What stakeholder theory is not. *Business Ethics Quarterly*, 13(4), 479–502. <https://doi.org/10.5840/beq200313434>
- Ringler, P., Keles, D., & Fichtner, W. (2016). Agent-based modelling and simulation of smart electricity grids and markets: A literature review. *Renewable and Sustainable Energy Reviews*, 57, 205–215. <https://doi.org/10.1016/j.rser.2015.12.169>

Wu, H.-H., Chatterjee, A., Clegg, N., et al. (2023). A new focused UDAR inversion to highlight finer geological features in transitional-resistivity formations. SPWLA Annual Logging Symposium. <https://doi.org/10.30632/SPWLA-2023-0069>.