

Article

Distributed Downhole Electric Heating as a Thermal-Control Element in Deep Steam-Assisted Gravity Drainage: Experimental Operating-Window Analysis for Heavy-Oil Recovery

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Abstract

Steam-assisted gravity drainage (SAGD) is constrained in deep heavy-oil reservoirs by wellbore heat losses, delayed steam-chamber development and high steam–oil ratio (SOR). This study develops an experimentally parameterized reduced-order screening framework for thermocable-assisted SAGD, formulated as a digital-twin prototype that couples heat transfer, temperature-dependent viscosity, chamber-growth geometry and energy-efficiency indicators. The formulation is evaluated within an experimentally parameterized screening matrix covering steam temperature, oil viscosity, permeability, depth, cable power and early heating time. The graphical dependencies are presented in a unified publication format and supplemented by heat-balance, chamber-field, sensitivity and operating-window analyses. For the reference experimental case, thermocable support increases oil rate from 84.1 to 96.1 t/day and reduces SOR from 2.70 to 2.30 t/t. The cable heat input is small relative to useful steam heat; therefore, its effect is interpreted through local compensation of downstream heat deficit and longitudinal temperature stabilization rather than through bulk energy addition. The strongest sensitivity is associated with steam rate, oil viscosity and depth, whereas cable power shows a beneficial but saturating effect. The proposed reduced-order digital-twin prototype is intended for feasibility screening, preliminary operating-window selection and prioritization of candidate regimes for detailed thermal-reservoir simulation and subsequent field-scale validation.

Keywords: steam-assisted gravity drainage; SAGD; thermocable; distributed electrical heating; heavy oil; thermal EOR; wellbore heat loss; steam chamber; reduced-order digital-twin prototype; energy efficiency; operating-window screening

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1. Introduction

The development of heavy-oil and natural-bitumen reservoirs requires a persistent compromise between production acceleration and thermal-energy consumption. Steam-assisted gravity drainage (SAGD) remains one of the most established thermal enhanced-

oil-recovery (EOR) technologies because it converts injected heat into viscosity reduction, steam-chamber expansion and gravity-driven drainage [1–4]. Its industrial attractiveness is therefore determined not only by the absolute volume of injected steam but also by how effectively this steam heat reaches the active drainage interval.

The governing physical chain is sequential and strongly coupled: steam injection transfers enthalpy to the well-reservoir system; the heated zone reduces oil viscosity; lower viscosity increases mobility; chamber geometry controls the effective drainage volume; and the process is finally evaluated through oil rate, cumulative production, SOR and energy consumption [5–7]. A weakness in any element of this chain reduces the overall efficiency. This is especially relevant for deep reservoirs and long horizontal sections, where a larger fraction of the steam enthalpy may be lost before it contributes to useful reservoir heating [8–10].

Conventional SAGD design usually focuses on steam pressure, steam temperature, well spacing, preheating duration and production constraints. These parameters are necessary but not always sufficient when longitudinal temperature attenuation becomes severe. If downstream sections of the producer remain underheated, gravity drainage becomes spatially uneven: part of the horizontal interval contributes actively to production, while other segments remain thermally inefficient. This creates a practical need for methods that redistribute heat rather than merely increase total steam injection [11,12].

In practice, SAGD efficiency can deteriorate when the steam chamber develops asymmetrically, when downstream parts of a long horizontal section remain below the effective viscosity-reduction temperature, or when additional steam injection increases losses faster than useful drainage. These bottlenecks are especially relevant in deep reservoirs, where wellbore heat loss, steam-quality degradation and delayed thermal communication can produce high SOR values even when nominal steam injection is sufficient. Under such conditions, the engineering problem is not only to increase the total heat input but to improve the spatial usefulness of delivered heat.

Practical thermal-efficiency improvements can be grouped into three categories: reducing parasitic heat losses, modifying the steam-chamber development path and adding auxiliary heat or solvent support near the drainage interval. Vacuum-insulated tubing and completion optimization primarily target the first category; solvent and electrical-heating approaches target the second and third categories. In this paper, a thermocable is defined as a distributed downhole electrical-heating cable installed along, or thermally coupled with, the horizontal interval. Unlike short local downhole heaters, it is treated as an extended spatial heat-placement element intended to reduce longitudinal underheating. Therefore, thermocable assistance is evaluated here as a spatial heat-placement method rather than as a substitute for steam injection [13,14].

The use of distributed electrical heat must nevertheless be evaluated carefully. If the cable is interpreted only as an additional bulk energy source, the expected production gain would be difficult to justify because cable power is usually small compared with the steam heat flux [15,16]. A more physically defensible hypothesis is that cable support improves the spatial usefulness of heat by compensating local cooling, reducing underheated segments and making the chamber-growth field more continuous along the horizontal well [17–20].

Existing studies on SAGD, electrical heating and digital-twin modeling provide important thermodynamic, experimental and engineering foundations, but they often address these components separately. Classical SAGD theory explains gravity drainage and chamber growth, but it does not directly quantify the local value of auxiliary heat placement along underheated horizontal sections. Wellbore heat-loss models describe thermal attenuation, but they are not usually coupled with SOR-oriented operating-window selec-

tion. Electrical-heating studies demonstrate near-wellbore thermal support, but the contribution of a small distributed electrical input to steam-use efficiency is often not separated from bulk heat addition. General digital-twin studies provide system-integration principles, but they rarely formulate a transparent thermal-EOR screening workflow that links heat delivery, viscosity transformation, chamber geometry and energy-efficiency indicators. Therefore, a compact reduced-order formulation is still needed to connect these mechanisms in a reproducible decision-support structure [21,22].

The scientific gap addressed in this paper is the absence of a transparent reduced-order screening framework for thermocable-assisted SAGD that simultaneously evaluates heat-transfer control, longitudinal underheating, chamber-development response, depth-dependent losses, SOR and total specific energy consumption [23,24]. Existing approaches either provide detailed full-physics reservoir simulation, which is not convenient for rapid operating-window screening, or use simplified correlations that do not explicitly resolve the spatial heat-placement role of distributed electrical heating [25–27].

The contribution of this work is threefold. First, thermocable assistance is formulated as a spatial heat-placement mechanism rather than as a dominant additional energy source. Second, the model connects steam heat delivery, wellbore loss, temperature-dependent viscosity, chamber geometry, oil-rate response and SOR through a common mass-and-energy accounting structure. Third, the operating regime is selected not by maximizing steam rate or cable power but by balancing oil-rate gain, SOR reduction, cable-power saturation and total specific energy consumption within a declared admissible screening domain [28–30].

The aim of this work is to develop and substantiate an experimentally parameterized reduced-order digital-twin prototype for thermocable-assisted SAGD in deep heavy-oil reservoirs. The specific objectives are to formalize steam heat delivery and wellbore loss compensation; define the thermocable as a distributed spatial heat-control element; quantify the effects of steam temperature, oil viscosity, permeability and depth; evaluate cable-power saturation; compare conventional and thermocable-assisted SAGD using oil rate and SOR; and identify candidate operating regimes for detailed thermal-reservoir simulation and subsequent field-scale validation [31–34].

This work is organized as follows. Section 2 describes the experimental-data structure, heat-balance equations, thermocable formulation, chamber-growth model and consistency checks. Section 3 reports the response of oil rate, SOR, temperature field, heat-loss index and operating-window indicators. Section 4 discusses the physical interpretation, engineering implications and validation pathway. Section 5 summarizes the main conclusions.

2. Materials and Methods

2.1. Digital-Twin Architecture and Modeling Scope

The proposed model is a reduced-order experimental–analytical screening framework formulated as a digital-twin prototype for thermocable-assisted SAGD. It is not a fully synchronized field digital twin with real-time data assimilation from an operating asset. Instead, it organizes reservoir descriptors, steam-operation conditions and thermocable parameters into an executable and reproducible calculation chain that includes heat balance, wellbore heat loss, temperature-dependent viscosity, mobility, chamber-growth geometry, SOR and energy-efficiency indicators. Therefore, the framework is intended for feasibility screening and operating-window selection before detailed thermal-reservoir simulation or pilot-scale validation [35,36]. The framework connects reservoir input data, a physics-based SAGD core, a distributed thermocable heat-control module, chamber-growth diagnostics and decision-oriented output indicators. Figure 1 summarizes the architecture.

The experimental data used for the formulation consist of three linked blocks: reservoir/well descriptors, steam-operation conditions and production/energy responses. The reservoir block includes depth, permeability, porosity, oil viscosity, initial reservoir temperature and well geometry. The steam-operation block contains steam temperature, steam rate and heat-delivery parameters. The thermocable block contains cable power, active coverage and heat-utilization efficiency. These blocks are kept separate until the heat-balance and chamber-growth equations are evaluated.

The input matrix used in this study is experimentally parameterized but should not be interpreted as a complete long-term field-history match. The fixed input values include reservoir and well descriptors, fluid-property ranges, steam-operation settings and thermocable technical parameters. These values were used to define the admissible screening domain. The response maps and three-dimensional surfaces reported in the Results section were then generated by the reduced-order model within this domain. Therefore, this manuscript distinguishes three data categories: fixed measured or experimentally assigned input points, interpolated response fields inside the screening domain and model-predicted performance indicators derived from the governing equations.

The modeling scope is deliberately bounded. The framework is used to compare physically admissible operating regimes within the declared admissible screening domain rather than to extrapolate outside the available ranges of depth, viscosity, permeability, steam temperature, steam quality, cable power and heating time. This distinction is important for reproducibility: every reported response is tied to an input range, a mass-balance rule and an explicit heat-transfer assumption.

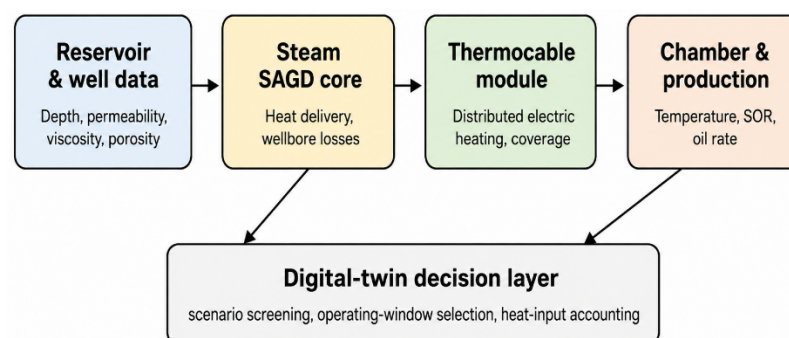


Figure 1. Architecture of the thermocable-assisted SAGD digital twin. The model links reservoir and well data, the steam-SAGD heat-transfer core, the distributed thermocable module, chamber-development diagnostics and decision-oriented outputs.

The architecture deliberately separates physical mechanisms from decision outputs. The reservoir block contains depth, permeability, porosity, oil viscosity, initial reservoir temperature and well geometry. The steam-SAGD core calculates useful heat delivery, wellbore losses and temperature-dependent mobility. The thermocable module modifies the longitudinal heat distribution through cable power, active length and utilization efficiency. The output layer reports oil rate, SOR, normalized heat-loss index, chamber-development indicators and operating-window metrics.

The term digital-twin prototype is used here in a restricted modeling sense: the framework is executable, parameterized and decision-oriented, but it does not claim real-time synchronization with a physical SAGD asset. This terminology is used to emphasize the integration of input states, thermal-response equations and engineering decision outputs within a single reproducible workflow [22–25,37]. Table 1 summarizes the functional blocks of the thermocable-assisted SAGD digital twin and clarifies how each block contributes to the calculation chain from input variables to operating-window indicators.

Table 1. Functional structure of the thermocable-assisted SAGD digital twin.

Block	Function
Input layer	Reservoir depth, permeability, porosity, oil viscosity, steam temperature, steam rate, well length and cable parameters.
Thermal core	Reduced heat-balance model for useful heat delivery, wellbore losses and active-zone temperature.
Thermocable module	Distributed electric heat source defined by linear power, active length, coverage and heat-utilization efficiency.
Chamber-growth block	Parametric description of steam-chamber height, longitudinal development and active drainage extent.
Performance outputs	Oil rate, SOR, heat-loss ratio, temperature profile, chamber geometry and operating-window indicators.

Table 1 shows that the model is organized as a chain of physically interpretable modules rather than as a black-box correlation. The separation of input, thermal core, cable module, chamber block and outputs make it possible to trace each performance indicator back to a specific heat-transfer or mobility mechanism.

2.2. Steam Thermodynamics and Useful Heat Delivery

The mathematical core is formulated so that the experimentally parameterized screening analysis remains reproducible and internally consistent. Steam and water thermodynamic properties were evaluated on the basis of IAPWS-IF97 steam/water property relations. In the reference calculation, the injected steam was treated on a saturated/wet-steam basis; therefore, steam pressure was linked to steam temperature through the saturation-pressure relation, while steam dryness was treated as an operating-quality input. For the reference case, the steam temperature was 260 °C, which corresponds to a saturated-steam pressure of approximately 4.7 MPa. Over the investigated steam-temperature interval of 220–300 °C, the corresponding saturated-pressure range is approximately 2.3–8.6 MPa. The reference steam dryness fraction was set to $x_s = 0.90$, and an uncertainty interval of $x_s = 0.85$ – 0.95 was used for sensitivity checking. If direct steam-quality measurements are available in a field pilot, x_s should be replaced by the measured separator or steam-generator quality value.

Steam mass rate is first converted from the daily operating basis to the SI unit used in the heat-balance calculation:

$$\dot{m}_s = \frac{M_s}{86,400}, \quad (1)$$

where M_s is the daily steam mass rate in kg/day and $\dot{m}_s$ is the steam mass flow rate in kg/s. The gross steam heat rate is then determined as

$$Q_s = \dot{m}_s \cdot \Delta h_s, \quad (2)$$

where Δh_s is the usable enthalpy drop of the injected steam. In a screening model, the enthalpy drop is represented as

$$\Delta h_s = h_s(T_s, x_s) - h_w(T_r), \quad (3)$$

where h_s is the steam specific enthalpy at steam temperature T_s and dryness fraction x_s , and h_w is the liquid-water specific enthalpy at reservoir temperature T_r . For saturated or wet steam, h_s was evaluated as $h_s(T_s, x_s) = h_f(T_s) + x_s h_{fg}(T_s)$, where h_f is

saturated-liquid enthalpy and h_{fg} is latent heat of vaporization. The steam pressure was taken as $p_s = p_{sat}(T_s)$. For superheated steam, h_s should instead be taken from the superheated-steam region at the specified pressure and temperature.

The value $\Delta h_s = 2.8$ MJ/kg used in the reference heat-balance table is therefore an equivalent screening value for high-quality injected steam under the reference thermal conditions. To avoid treating it as an exact universal constant, the revised analysis interprets this value as the baseline enthalpy-drop assumption and checks the heat-balance sensitivity over $\Delta h_s = 2.55$ – 2.85 MJ/kg.

The useful heat delivered to the active drainage zone is defined as

$$Q_{\text{use}} = \eta_s \cdot Q_s + \eta_c \cdot Q_c, \quad (4)$$

where η_s is the steam-delivery efficiency, η_c is the cable heat-utilization coefficient and Q_c is the distributed electrical heat input. These coefficients are not treated as universal constants. In the reference case, $\eta_s = 0.68$ was used for conventional SAGD and $\eta_s = 0.70$ for the thermocable-assisted case to represent a modest improvement in useful heat delivery caused by longitudinal temperature stabilization. The cable heat-utilization coefficient was set to $\eta_c = 0.85$ in the reference calculation. Sensitivity checks were performed over $\eta_s = 0.65$ – 0.72 and $\eta_c = 0.75$ – 0.90 . The thermal efficiency of steam delivery is

$$\eta_s = \frac{Q_{s,\text{use}}}{Q_s} = 1 - \frac{Q_{\text{loss}}}{Q_s}. \quad (5)$$

2.3. Wellbore Heat-Loss Model

The wellbore heat-loss model separates dimensional heat-transfer quantities from normalized loss indicators used in operating-regime comparison. The instantaneous dimensional heat loss is expressed as

$$Q_{\text{loss}} = U \cdot A_w \cdot \Delta T, \quad (6)$$

where U is the overall heat-transfer coefficient, A_w is the effective heat-transfer area and ΔT is the temperature difference between the wellbore and the surrounding formation. The total thermal resistance is approximated by

$$R_{\text{total}} = R_{\text{pipe}} + R_{\text{ins}} + R_{\text{cem}} + R_{\text{rock}}, \quad (7)$$

with pipe, insulation, cement and rock contributions. The corresponding overall heat-transfer coefficient is

$$U = \frac{1}{R_{\text{total}}}. \quad (8)$$

For a local wellbore segment, the longitudinal loss rate is written as

$$q_{\text{loss}}(z) = U(z) \cdot \pi D_w \cdot [T_s(z) - T_r], \quad (9)$$

where z is the measured depth and D_w is the wellbore diameter. For experimental-regime visualization, dimensional losses are converted into a normalized heat-loss index:

$$I_{\text{loss}} = \frac{Q_{\text{loss}}}{Q_{\text{loss,ref}}}. \quad (10)$$

This distinction prevents ambiguity between real heat loss in MW and a dimensionless indicator used for relative comparison.

2.4. Thermocable Heat-Source Formulation

The thermocable is not modeled as a large additional bulk heat source. It is modeled as a spatially distributed heat-control element placed close to the horizontal section:

$$Q_c = q_c \cdot L_c \cdot \chi_c, \quad (11)$$

where q_c is cable linear power, L_c is cable length and χ_c is the active coverage factor. The local distribution of cable heat is

$$q_c(s) = q_{c0} \cdot I(s \in \Omega_c), \quad (12)$$

where z is the measured coordinate along the horizontal section and $I(z \in \Omega_c)$ is an indicator function equal to 1 inside the cable-covered interval and 0 outside it. In the reference case, $\Omega_c = [z_1, z_2] = [60, 740]$ m, which corresponds to an effective active coverage of 680 m over the 800 m horizontal interval. The temperature increment produced by cable support is represented as

$$\Delta T_c(z, t) = A_c \left[1 - \exp\left(-\frac{t}{\tau_c}\right) \right] \exp\left[-\frac{(z - z_c)^2}{2\sigma_c^2}\right], \quad (13)$$

where $\Delta T_c(z, t)$ is the cable-induced temperature increment, °C; A_c is the local temperature-amplitude parameter, °C; t is the heating time, h; τ_c is the thermal response time, h; z is the measured coordinate along the horizontal section, m; z_c is the center of the cable-influence zone, m; and σ_c is the longitudinal smoothing scale, m.

The Gaussian-type term in Equation (13) is used as a reduced-order spatial smoothing kernel. It does not claim to resolve detailed microscopic conduction around the cable. Instead, it approximates how a distributed downhole electrical heater produces a localized but longitudinally smoothed temperature increment around the cable-covered interval.

To avoid comparing cable power only with total steam heat, a local compensation ratio was introduced. This ratio compares useful cable heat with the local heat deficit in the cable-covered section rather than with the whole-field steam heat input:

$$\chi_{\text{loc}}(z) = \frac{q_{\text{loss,base}}(z) - q_{\text{loss,assist}}(z) + \varepsilon_q}{q_{c,\text{useful}}(z)}, \quad (14)$$

where $\chi_{\text{loc}}(z)$ is the local thermocable compensation ratio, dimensionless; $q_{c,\text{useful}}(z)$ is the useful cable heat supplied per unit length at coordinate z , W/m; $q_{\text{loss,base}}(z)$ is the baseline local heat-loss or heat-deficit rate without cable assistance, W/m; $q_{\text{loss,assist}}(z)$ is the residual local heat-loss or heat-deficit rate under thermocable assistance, W/m; and ε_q is a small numerical stabilizer used only to avoid division by zero in zones with negligible local heat deficit.

Thus, $\chi_{\text{loc}}(z)$ does not state that the cable replaces a large fraction of total steam heat. It evaluates whether the cable is large enough to affect the local downstream heat deficit that limits viscosity reduction and chamber continuity. This is the relevant scale for interpreting the leverage effect of a small distributed electrical input.

The physical role of the thermocable is clarified in Figure 2. The figure illustrates why the cable contribution is interpreted at the local downstream heat-deficit scale rather than as a bulk replacement for steam energy.

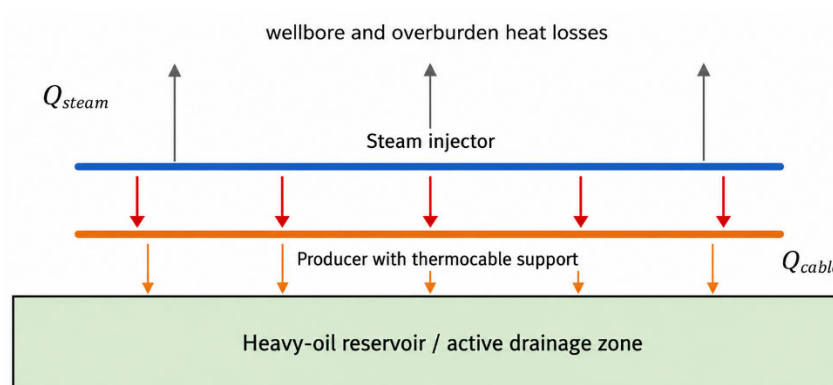


Figure 2. Heat-delivery concept for thermocable-assisted SAGD. The thermocable is evaluated against the local downstream heat deficit rather than against total useful steam heat; its role is to stabilize the longitudinal temperature field and reduce underheated intervals along the horizontal section.

2.5. Temperature Field and Viscosity Transformation

The temperature field links heat delivery with viscosity reduction and therefore with oil mobility. The governing reduced energy equation is

$$(\rho C_p)_{\text{eff}} \frac{\partial T}{\partial t} = \nabla \cdot (k_{\text{eff}} \nabla T) + Q_s(z, t) + Q_c(z, t) - Q_{\text{loss}}(z, t), \quad (15)$$

where $(\rho C_p)_{\text{eff}} \frac{\partial T}{\partial t}$ is the effective volumetric heat capacity of the porous medium, J/(m³·K); T is the temperature, °C; t is the time, s or h depending on the implemented calculation step; k_{eff} is the effective thermal conductivity, W/(m·K); $Q_s(z, t)$ is the distributed steam-related heat source term; $Q_c(z, t)$ is the distributed thermocable heat-source term; and $Q_{\text{loss}}(z, t)$ is the wellbore and formation heat-loss term.

In the reduced-order implementation, $Q_c(z, t)$ is linked to the cable-covered interval Ω_c and the temperature increment in Equation (13), while $Q_s(z, t)$ represents the useful steam heat distributed over the active chamber-development zone. This source-term representation is used for screening and should be replaced by a detailed coupled wellbore–reservoir model in field-scale design.

The effective volumetric heat capacity is determined as

$$\rho_{\text{eff}} c_{\text{eff}} = (1 - \phi) \rho_r c_r + \phi S_o \rho_o c_o + \phi S_w \rho_w c_w, \quad (16)$$

and the effective thermal conductivity is approximated by

$$\lambda_{\text{eff}} = (1 - \phi) \lambda_r + \phi S_o \lambda_o + \phi S_w \lambda_w. \quad (17)$$

For the longitudinal screening calculation, the temperature along the horizontal well is

$$T(s, t) = T_r + (T_s - T_r) \left[1 - \exp\left(-\frac{t}{\tau_T}\right) \right] \exp\left(-\frac{s}{L_T}\right) + \Delta T_c(s, t). \quad (18)$$

The viscosity transformation is then modeled by an exponential law:

$$\mu_{\text{eff}} = \mu(T_{\text{eff}}) = \mu_0 \exp[-b_\mu (T_{\text{eff}} - T_0)], \quad (19)$$

where μ_{eff} is the effective heated-oil viscosity used in the mobility and oil-rate equations, mPa·s; $\mu(T_{\text{eff}})$ is the oil viscosity at the effective heated-zone temperature, mPa·s; μ_0 is the oil viscosity at the reference reservoir temperature T_0 , mPa·s; T_{eff} is the effective heated-zone temperature, °C; T_0 is the reference reservoir temperature, °C; and b_μ is the temperature-sensitivity coefficient of heavy-oil viscosity, °C⁻¹, with a sensitivity interval of 0.020–0.035 °C⁻¹ used to represent uncertainty in the heavy-oil viscosity–temperature relation. This parameter should be fitted from measured viscosity–temperature data for the target heavy oil.

2.6. Mobility and Oil-Rate Response

Oil-rate response is not treated as a direct empirical function of steam rate. It is derived from the mobility increase caused by heating. Oil mobility is

$$\lambda_o(T) = \frac{k \cdot k_{ro}}{\mu_o(T)}, \quad (20)$$

and the effective chamber temperature is

$$T_{\text{eff}}(t) = \frac{1}{V_{\text{ch}}} \int_{V_{\text{ch}}} T(x, y, z, t) dV. \quad (21)$$

The oil-rate response is represented as

$$q_o = q_{\text{ref}} \left(\frac{k}{k_{\text{ref}}} \right)^{\alpha_k} \left(\frac{\mu_{\text{ref}}}{\mu_{\text{eff}}} \right)^{\beta_\mu} \left(\frac{H_{\text{ch}}}{H_{\text{ref}}} \right)^{\gamma_H} F_{ch} F_c, \quad (22)$$

where q_o is the oil-rate response, t/day; $q_{\text{ref}} = 84.1$ t/day is the reference conventional SAGD oil rate; k is permeability, mD; $k_{\text{ref}} = 1000$ mD; μ_{eff} is effective heated-oil viscosity, mPa·s; $\mu_{\text{ref}} = 700$ mPa·s; H_{ch} is chamber height, m; $H_{\text{ref}} = 18$ m; $\alpha_k, \beta_\mu, \gamma_H$ are fitted screening exponents; F_{ch} is a chamber-shape factor; and F_c is the thermocable-supported temperature-stabilization factor. The normalized form in Equation (22) was introduced to avoid an opaque dimensional calibration coefficient. The reference oil rate q_{ref} anchors the calculation to the conventional SAGD reference case, while the permeability, viscosity and chamber-height ratios express relative changes within the admissible screening domain.

2.7. Steam-Chamber Geometry

The steam chamber is described by a reduced-order parametric geometry. The purpose of this block is not to reproduce all local heterogeneity, shale barriers, or three-phase flow effects but to provide a geometrically consistent screening relation between heat delivery, permeability, viscosity, thermocable-supported temperature stabilization and active drainage volume. Chamber height is

$$H_{\text{ch}}(t) = H_{\text{max}} [1 - \exp(-a_H t)] F_k F_\mu F_c, \quad (23)$$

while chamber width is

$$W_{\text{ch}}(t) = W_{\text{max}} [1 - \exp(-a_W t)] F_k F_\mu F_c. \quad (24)$$

The active chamber volume is approximated as

$$V_{\text{ch}}(t) = \frac{\pi}{4} H_{\text{ch}}(t) W_{\text{ch}}(t) L_{\text{ch}}(t), \quad (25)$$

and the corresponding cross-sectional chamber area is

$$A_{\text{ch}}(t) = \frac{\pi}{4} H_{\text{ch}}(t) W_{\text{ch}}(t), \quad (26)$$

where H_{ch} and W_{ch} are chamber height and width, m; H_{max} is the maximum admissible chamber height bounded by net oil-saturated thickness; W_{max} is the maximum admissible chamber width used in the reduced-order geometric closure; a_H and a_W are chamber-height and chamber-width growth coefficients, h^{-1} ; F_k, F_μ, F are permeability, viscosity and thermocable correction factors; $L_{\text{ch}}(t)$ is the active heated chamber length, m; V_{ch} is chamber volume, m^3 ; and A_{ch} is cross-sectional chamber area, m^2 .

The elliptical cross-section in Equations (25) and (26) is a reduced-order geometric closure. It is used because it preserves a consistent relation between chamber height, chamber width, area and volume while keeping the model suitable for rapid screening. The limitation is that local heterogeneity, steam override, shale barriers, local conformance effects and detailed three-phase flow are not resolved. Therefore, V_{ch} and A_{ch} are interpreted as relative chamber-development indicators rather than field-scale volumetric forecasts.

2.8. SOR, Total Specific Energy Consumption and Operating-Window Objective

Steam-oil ratio (SOR) was retained as the primary steam-use metric. To avoid mixing cumulative and instantaneous quantities, SOR was calculated from steam and oil masses over the same time interval. When daily rates are reported, they are interpreted as daily mass equivalents over the same interval:

$$\text{SOR} = \frac{M_{o,\Delta t}}{M_{s,\Delta t}} = \frac{\dot{M}_{o,\text{day}}}{\dot{M}_{s,\text{day}}}, \quad (27)$$

where $M_{s,\Delta t}$ is the steam mass injected over the considered interval Δt , t; $M_{o,\Delta t}$ is the oil mass produced over the same interval, t; $\dot{M}_{o,\text{day}}$ is the daily steam mass used for the mass-balance calculation, t/day; and $\dot{M}_{s,\text{day}}$ is the daily oil mass, t/day. The second equality is used only when both steam and oil are reported on the same daily basis.

Because the thermocable consumes electricity, steam efficiency alone is not sufficient for evaluating thermocable-assisted SAGD [38]. The total specific energy consumption was therefore calculated by combining the steam heat supplied over the considered interval with the electrical energy consumed by the cable over the same interval:

$$\text{SEC}_{\text{tot}} = \frac{Q_{s,\Delta t} + E_{c,el,\Delta t}}{M_{o,\Delta t}}, \quad (28)$$

where SEC_{tot} is the total specific energy consumption, MJ/t or GJ/t; $Q_{s,\Delta t}$ is the total steam heat supplied during the considered interval, MJ or GJ; $E_{c,el,\Delta t}$ is the electrical energy consumed by the thermocable during the same interval, MJ or GJ; and $M_{o,\Delta t}$ is the produced oil mass over the same interval, t.

If the calculation is implemented using average powers, then $Q_{s,\Delta t} = \bar{Q}_s \Delta t$ and $E_{c,el,\Delta t} = \bar{P}_{c,el} \Delta t$. Thus, the steam and electrical terms are evaluated over the same time basis as oil production.

For comparative screening, an additional dimensionless energy-efficiency index was introduced. It compares the useful oil-production response with the combined steam and electrical energy input:

$$EEI = \frac{SEC_{\text{tot}} / SEC_{\text{ref}}}{q_o / q_{\text{ref}}}, \quad (29)$$

where EEI is the dimensionless energy-efficiency index; q_o is the oil-rate response for the considered operating case, t/day; q_{ref} is the reference conventional SAGD oil rate, t/day; SEC_{tot} is the total specific energy consumption for the considered case; and SEC_{ref} is the total specific energy consumption of the reference conventional SAGD case.

For operating-window screening, a normalized objective function was used. The objective penalizes high steam use and high cable power while rewarding oil-rate improvement. The normalized variables were defined relative to the admissible screening-domain bounds:

$$q_o^* = \frac{q_o - q_{\min}}{q_{\max} - q_{\min}}, \quad SOR^* = \frac{SOR - SOR_{\min}}{SOR_{\max} - SOR_{\min}}, \quad P_c^* = \frac{q_{c'}}{q_{c,\max'}}, \quad (30)$$

where q_o^* is the normalized oil-rate indicator; SOR^* is the normalized steam-use indicator; P_c^* is the normalized cable-power indicator; q_o is the oil rate, t/day; $q_{\min}$ and $q_{\max}$ are lower and upper oil-rate bounds in the screening domain, t/day; $SOR_{\min}$ and $SOR_{\max}$ are lower and upper SOR bounds in the screening domain, t/t; $q_{c'}$ is the cable linear power, W/m; and $q_{c,\max'}$ is the maximum admissible cable linear power, W/m.

$$J = w_1 q_o^* - w_2 SOR^* - w_3 P_c^*, \quad w_1 + w_2 + w_3 = 1, \quad (31)$$

where J is the dimensionless operating-window objective; w_1, w_2, w_3 are weighting coefficients assigned to oil-rate benefit, SOR penalty and cable-power penalty, respectively.

In the reference screening calculation, $w_1 = 0.40$, $w_2 = 0.40$, and $w_3 = 0.20$. Equal priority was assigned to oil-rate improvement and SOR reduction, whereas cable power was given a smaller but non-zero weight because the thermocable is an auxiliary spatial heat-control element rather than the dominant energy source. A weight-sensitivity check was performed by varying each weight by ± 0.10 while preserving $w_1 + w_2 + w_3 = 1$. The preferred operating region remained in the moderate steam-rate and moderate cable-power interval.

The admissible operating window was constrained by minimum oil-rate, maximum SOR, maximum steam-temperature and maximum cable-power criteria:

$$q_o \geq q_{\min}, \quad SOR \leq SOR_{\max}, \quad T_s \leq T_{\max}, \quad q_{c'} \leq q_{c,\max'}, \quad (32)$$

where $q_{\min} = 94$ t/day is the minimum oil-rate threshold used in the reference screening; $SOR_{\max} = 2.45$ t/t is the maximum admissible steam-oil ratio; $T_{\max} = 300$ °C is the upper

steam-temperature bound of the screening domain; and $q_{c,\max}' = 60$ W/m is the maximum admissible cable linear power.

These thresholds are not universal design limits. They define the reference admissible screening domain used to identify candidate thermocable-assisted SAGD regimes for further simulation or pilot validation.

2.9. Experimental-Data Consistency and Physical-Plausibility Checks

The model outputs were screened using a mass-balance consistency rule that prevents incompatible combinations of steam mass, oil mass and SOR from being reported. The consistency check was applied to all paired conventional and thermocable-assisted cases:

$$\left| \text{SOR} - \frac{M_{o,\Delta t}}{M_{s,\Delta t}} \right| \leq \epsilon_{\text{SOR}}, \quad (33)$$

where $\epsilon_{\text{SOR}} = 0.03$ t/t is the numerical tolerance used in the reference analysis. This value corresponds to approximately 1–1.5% of the reference SOR range and was used to reject internally inconsistent combinations of steam mass, oil mass and reported SOR.

In addition, dimensional heat-loss reductions were required to remain compatible with the useful cable heat reported in the heat-balance table. When a loss reduction is shown as a relative operating-regime effect, it is reported as a normalized heat-loss index rather than as a direct MW reduction. This prevents the local heat-placement effect of the thermocable from being misinterpreted as a large bulk-energy contribution [39,40].

2.10. Uncertainty Propagation and Statistical Interpretation

Because the present study is a reduced-order screening analysis rather than a repeated long-term field trial, the reported uncertainty bounds are interpreted as propagated engineering uncertainty rather than as formal field-statistical confidence intervals. The uncertainty analysis was introduced to test whether the main reference-case differences are larger than plausible measurement and parameter uncertainty [41].

The following relative or absolute uncertainty levels were used in the reference propagation: steam mass, $\pm 2.0\%$; oil rate, $\pm 3.0\%$; downstream temperature estimate, ± 5 – 7 °C depending on the operating case; normalized heat-loss index, ± 0.04 ; steam dryness fraction, $x_s = 0.90$ with a sensitivity interval of 0.85–0.95; steam-delivery efficiency, $\eta_s = 0.65$ – 0.72 ; and cable heat-utilization coefficient, $\eta_c = 0.75$ – 0.90 . The uncertainty levels are used for screening robustness checks and should be replaced by site-specific instrument uncertainty and repeatability estimates when pilot data become available.

For a ratio-type metric such as SOR, the relative uncertainty was propagated as

$$u(\text{SOR}) = \sqrt{\left(\frac{u(M_s)}{M_s} \right)^2 + \left(\frac{u(M_o)}{M_o} \right)^2}, \quad (34)$$

where $u(\text{SOR})$ is the standard uncertainty of SOR, $u(M_s)$ is the steam-mass uncertainty, $u(M_o)$ is the oil-mass uncertainty, M_s is the steam mass and M_o is the oil mass over the same time interval. For paired differences, the uncertainty of the difference was estimated as

$$\sqrt{u(y_1)^2 + u(y_2)^2}, \quad (35)$$

where y_1 and y_2 are the compared conventional and thermocable-assisted values. A difference was interpreted as screening-significant when its magnitude exceeded the propagated uncertainty of the paired difference. This criterion is not a substitute for repeated field-trial statistics, but it prevents overinterpretation of small model differences [42–45].

2.11. Experimentally Parameterized Screening Matrix and Unit-Consistency Procedure

A structured experimentally parameterized screening matrix was used to evaluate the reduced-order model. The matrix included fixed input points for one-factor sweeps, paired conventional/cable-assisted comparisons and cross-regime cases combining shallow/deep reservoirs, low/high viscosity and low/high permeability. The input variables were treated as measured, experimentally assigned, or technically specified values, whereas the response maps, contour fields and three-dimensional surfaces were model-interpolated or model-predicted within the declared admissible screening domain. All response values were processed in consistent mass and energy units: daily steam mass was converted to kg/s for heat-balance calculations, oil rate was retained in t/day for operational interpretation and SOR was determined only from the corresponding steam and oil masses according to Equation (27).

The experimental design, sensitivity ranking and operating-window interpretation follow standard principles of statistical learning, surrogate modeling, sensitivity analysis and multi-objective screening [46–48]. Related author-team studies provide additional background on SAGD profitability, enhanced-oil-recovery screening, unconventional-resource drainage, energy-efficient process stability, optimal control of energy-intensive equipment, hybrid power-system support, autonomous power supply and BESS-supported field microgrids [49,50]. Table 2 defines the admissible screening domain used for the experimentally parameterized analysis. The selected ranges cover the principal thermal, geological and thermocable-control variables used to compare physically admissible regimes within the reduced-order screening model.

Table 2. Admissible screening domain used in the experimentally parameterized analysis.

Parameter	Range	Role in Model
Steam temperature	220–300 °C	Controls heat-transfer potential and viscosity reduction.
Initial oil viscosity	300–1500 mPa·s	Defines mobility limitation in heavy-oil conditions.
Permeability	250–2000 mD	Controls filtration capacity of the heated oil.
Vertical depth	500–1500 m	Controls heat-loss exposure and steam-delivery penalty.
Cable linear power	0–60 W/m	Controls distributed electrical heating along the horizontal interval.
Heating time	48–240 h	Controls early thermal-response and initial chamber-growth tendency; not used as a full SAGD lifetime forecast.

The admissible screening domain in Table 2 defines the limits of interpretation. The 48–240 h heating-time interval is used only to compare early thermal response, longitudinal temperature stabilization and initial chamber-growth tendency. It is not interpreted as a full SAGD project duration or as a long-term cumulative recovery forecast. Extrapolation to colder, deeper, thinner, more heterogeneous, or longer-term field conditions requires recalibration, detailed thermal-reservoir simulation and field-history validation. Table 3 provides the reference case used for the direct comparison between conventional SAGD and thermocable-assisted SAGD. These values fix the reservoir geometry, fluid properties, steam conditions and cable parameters before the performance indicators are compared.

Table 3. Reference case for thermocable-assisted SAGD comparison.

Input	Reference Value
Vertical depth	1000 m
Horizontal length	800 m
Net oil-saturated thickness	25 m
Porosity	0.30
Permeability	1000 mD
Initial oil viscosity	700 mPa·s
Reservoir temperature	40 °C
Steam temperature	260 °C
Steam-pressure basis	Saturated-steam pressure at 260 °C, approximately 4.7 MPa
Steam dryness fraction	$x_s = 0.90$ reference value; 0.85–0.95 sensitivity interval
Equivalent steam enthalpy drop	$\Delta h_s = 2.8$ MJ/kg reference value; 2.55–2.85 MJ/kg sensitivity interval
Nominal steam rate	225 t/day reference design basis
Steam-delivery efficiency	$\eta_s = 0.68$ conventional; $\eta_s = 0.70$ thermocable-assisted; 0.65–0.72 sensitivity interval
Cable linear power	45 W/m
Cable active coverage	0.85
Cable heat-utilization coefficient	$\eta_c = 0.85$ reference value; 0.75–0.90 sensitivity interval

The reference case in Table 3 is used as the baseline for all direct conventional-versus-assisted comparisons. In the revised table, the reservoir geometry, fluid properties, steam-temperature basis, steam-pressure basis, dryness fraction, equivalent enthalpy drop and heat-utilization coefficients are reported together to make the heat-balance assumptions reproducible. Keeping these reference conditions fixed allows the thermocable contribution to be evaluated without mixing it with unrelated changes in geology, steam quality, or operating pressure.

To improve reproducibility, the main reduced-order parameters used in the thermocable-temperature, viscosity, oil-rate and chamber-growth submodels are summarized in Table 4. The table separates measured or fixed input quantities from fitted screening coefficients and assigned closure parameters. These values are not universal reservoir constants; they define the reference screening case and should be recalibrated when field temperature profiles, pressure data, steam-quality logs and production histories become available.

Table 4. Reduced-order parameter definitions, reference values and calibration status.

Parameter	Unit	Reference Value or Range	Status	Role in Model
q'_c	W/m	45	Technically specified	Cable linear power used to calculate distributed electrical input
L_h	m	800	Fixed input	Horizontal interval length
χ_c	dimensionless	0.85	Technically specified	Active cable-coverage factor
$L_c = \chi_c L_h$	m	680	Derived	Effective cable-covered length
$\Omega_c = [z_1, z_2]$	m	[60, 740]	Assigned reference interval	Cable-covered interval along the horizontal coordinate (z)
A_c	°C	35 reference; 20–45 sensitivity interval	Fitted screening coefficient	Local cable-induced temperature-amplitude parameter in Equation (13)
τ_c	h	72 reference; 48–120 sensitivity interval	Fitted screening coefficient	Thermal response time of cable-induced temperature rise

z_c	m	500 reference	Assigned from cable-placement geometry	Center of the longitudinal cable-influence zone
σ_c	m	200 reference; 150–250 sensitivity interval	Fitted/assigned smoothing parameter	Longitudinal smoothing scale of the distributed cable-temperature response
b_μ	$^{\circ}\text{C}^{-1}$	0.025 reference; 0.020–0.035 sensitivity interval	Fitted from viscosity–temperature behavior	Temperature-sensitivity coefficient in the exponential viscosity law
q_{ref}	t/day	84.1	Reference calibration point	Conventional SAGD oil rate used for normalized oil-rate response
k_{ref}	mD	1000	Reference input	Reference permeability for normalized oil-rate response
μ_{ref}	mPa·s	700	Reference input	Reference initial oil viscosity
H_{ref}	m	18	Fitted screening value	Reference chamber-height scale used in the normalized oil-rate response
α_k	dimensionless	0.35	Fitted screening exponent	Permeability exponent in normalized oil-rate response
β_μ	dimensionless	0.50	Fitted screening exponent	Viscosity/mobility exponent in normalized oil-rate response
γ_H	dimensionless	0.65	Fitted screening exponent	Chamber-height exponent in normalized oil-rate response
H_{max}	m	25	Fixed by net oil-saturated thickness	Maximum admissible steam-chamber height
W_{max}	m	70	Assigned geometric closure	Maximum admissible chamber width in the reduced-order chamber model
a_H	h^{-1}	0.018	Fitted screening coefficient	Chamber-height growth coefficient
a_W	h^{-1}	0.010	Fitted screening coefficient	Chamber-width growth coefficient
F_k	dimensionless	$\left(\frac{k}{k_{\text{ref}}}\right)^{0.25}$	Model closure factor	Permeability correction for chamber growth
F_μ	dimensionless	$\left(\frac{\mu_{\text{ref}}}{\mu_{\text{eff}}}\right)^{0.20}$	Model closure factor	Viscosity correction for chamber growth
F_c	dimensionless	1.00 conventional; 1.03–1.08 thermocable-assisted	Fitted/assigned correction factor	Thermocable-supported temperature-stabilization factor
$L_{ch}(t)$	m	$L_h[1 - \exp(-a_L t)]$, $a_L = 0$	Reduced-order closure	Active heated chamber length along the horizontal interval

Table 4 makes the calibration status of the reduced-order model explicit. The thermocable-temperature parameters A_c , τ_c , z_c and σ_c control the spatial and temporal smoothing of the cable-induced temperature increment. The viscosity coefficient β_μ , the normalized oil-rate exponents and the chamber-growth coefficients define the response of oil mobility and chamber geometry within the admissible screening domain. These parameters should not be transferred to another reservoir as fixed constants; they require recalibration against viscosity–temperature measurements, downhole

temperature profiles, steam-quality data and production-history observations before field-scale operational use.

Table 5 presents the cross-regime matrix used to verify mass-balance consistency and to interpret the operating window under shallow, reference, deep and high-viscosity conditions. In Table 5, the effective steam rate is not an independently predicted production output. It is the scenario-specific steam mass used in the SOR mass-balance calculation after accounting for the selected operating case, heat-delivery efficiency and admissible-regime constraints. The nominal steam rate in Table 3 is retained as the reference design basis, whereas the effective steam rates in Table 5 are the consistent steam-mass inputs used to compare conventional and thermocable-assisted cases on the same SOR basis.

Table 5. Cross-operating matrix used for mass-and-energy consistency testing and operating-window interpretation.

Scenario	Depth, m	Viscosity, mPa·s	Cable Power, W/m	Effective Steam Mass Used for SOR, t/day	Oil Rate, t/day	SOR, t/t	Interpretation
S1: shallow conventional	500	700	0	196.0	98.0	2.00	Low depth penalty
S2: shallow cable-assisted	500	700	45	190.6	104.7	1.82	Limited but positive cable benefit
S3: reference conventional	1000	700	0	227.1	84.1	2.70	Baseline comparison
S4: reference cable-assisted	1000	700	45	221.0	96.1	2.30	Spatial heat-supported drainage
S5: deep conventional	1500	700	0	235.2	73.5	3.20	High heat-loss penalty
S6: deep cable-assisted	1500	700	45	229.1	88.1	2.60	Largest relative cable benefit
S7: high-viscosity conventional	1000	1500	0	226.8	75.6	3.00	Mobility-limited case
S8: high-viscosity cable-assisted	1000	1500	45	217.4	83.6	2.60	Cable support partially offsets mobility penalty

The cross-regime matrix in Table 5 is especially important for avoiding a single-case conclusion. It shows that the thermocable effect is not uniform across the experimental operating cases: the relative benefit increases when depth or viscosity makes conventional SAGD less thermally efficient. The values in Table 5 should therefore be interpreted as a mass-and-energy consistency matrix rather than as independent field-production measurements. This distinction is important because the same reference reservoir may be evaluated under different steam-delivery and thermocable-support assumptions while retaining a consistent SOR definition.

Four verification checks were applied before interpreting the results. First, all outputs were screened for physically admissible ranges. Second, monotonic trends were checked for variables with expected directional behavior, such as steam temperature, viscosity and permeability. Third, SOR was cross-checked against the steam/oil mass balance in Equation (33). Fourth, thermocable-related heat-loss changes were interpreted as either dimensional heat terms or normalized heat-loss indices but not mixed in the same table.

3. Results

To clarify the status of the results, the figures in this section distinguish fixed matrix points from interpolated or model-predicted response fields. The plotted response surfaces and contour maps should be interpreted as reduced-order screening outputs within the admissible screening domain rather than as direct long-term field-history measurements. Where paired reference-case values are compared, the interpretation is supported by propagated engineering uncertainty rather than by formal repeated-field-trial statistics. The corresponding uncertainty bounds are reported in Table 6.

Table 6. Reference-case comparison of conventional and thermocable-assisted SAGD with propagated engineering uncertainty.

Indicator	Conventional SAGD	Thermocable-Assisted SAGD	Difference	Screening Interpretation
Effective steam mass used for SOR, t/day	227.1 ± 4.5	221.0 ± 4.4	-6.1 t/day (-2.7%)	Scenario-specific steam-mass basis used for SOR consistency
Oil rate, t/day	84.1 ± 2.5	96.1 ± 2.9	$+12.0 \pm 3.8$ t/day ($+14.3\%$)	Increase exceeds propagated paired uncertainty
SOR, t/t	2.70 ± 0.09	2.30 ± 0.08	-0.40 ± 0.12 t/t (-14.8%)	Reduction exceeds propagated paired uncertainty
Estimated downstream measured-depth temperature, °C	116 ± 6	151 ± 7	$+35 \pm 9$ °C	Temperature increase exceeds propagated estimate uncertainty
Normalized heat-loss index, dimensionless	1.00 ± 0.04	0.87 ± 0.04	-0.13 ± 0.06 (-13.0%)	Reduction is larger than the propagated index uncertainty
Interpretation	Baseline thermal drainage	Spatial heat-supported drainage	Higher useful heat distribution	Screening-level comparison, not a repeated field-trial statistic

3.1. Steam-Temperature Response

Figure 3 reformulates the steam-temperature sensitivity test as a coupled temperature-quality response map. This presentation is less vulnerable to one-factor overinterpretation because steam temperature, steam quality, oil-rate response and SOR are evaluated together within the same operating domain.

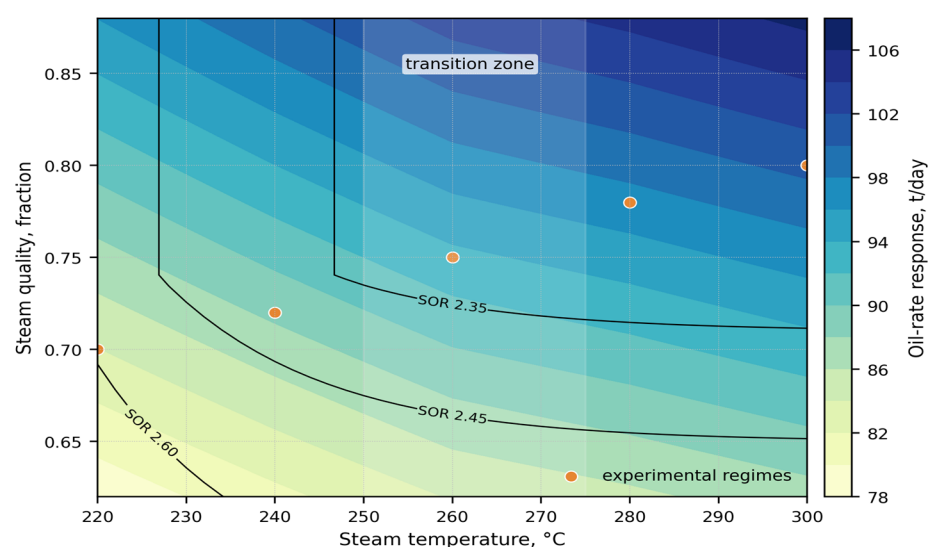


Figure 3. Coupled steam-temperature and steam-quality response map. Color indicates oil-rate response, while contour labels show SOR; the map demonstrates that the temperature effect must

be interpreted together with steam quality rather than as an isolated one-factor trend. Fixed matrix points are shown as markers; the color field is the model-interpolated response within the admissible screening domain.

The transition zone in Figure 3 is important for engineering interpretation. For the reference viscosity, permeability, depth and steam-quality assumptions, the useful effect of steam temperature approaches a plateau within approximately 250–270 °C. This interval should not be interpreted as a universal SAGD threshold; it is specific to the declared admissible screening domain and should be recalibrated for other reservoir and steam-quality conditions.

3.2. Oil Viscosity and Permeability Effects

Oil viscosity and permeability must be interpreted jointly because viscosity controls flow resistance, whereas permeability controls the ability of the heated oil to drain toward the producer. Figure 4 therefore replaces the simple viscosity sweep with a two-parameter mobility field.

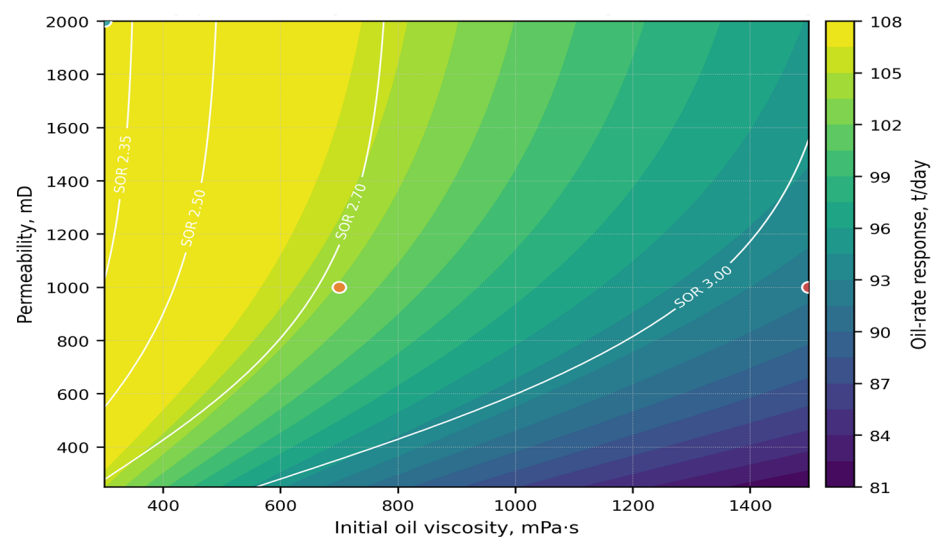


Figure 4. Viscosity–permeability interaction map for oil-rate response and SOR. The figure replaces a one-factor viscosity curve with a two-parameter mobility field and shows how permeability can partly compensate for the negative effect of high initial viscosity. Fixed matrix points are shown as markers; the color field is the model-interpolated response within the admissible screening domain.

Figure 5 extends the permeability analysis by adding reservoir depth as a second controlling parameter. This is necessary because permeability improves filtration capacity, whereas depth increases heat-loss exposure and reduces the useful fraction of delivered heat.

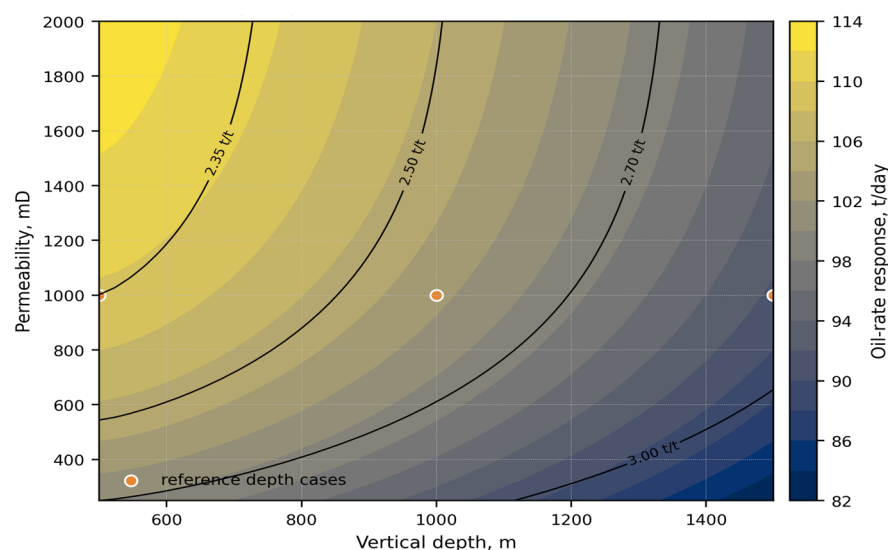


Figure 5. Permeability–depth interaction map for the conversion of delivered heat into oil-rate response. The figure shows that the same permeability value has different production meaning under shallow and deep heat-loss conditions. Fixed matrix points are shown as markers; the color field is the model-interpolated response within the admissible screening domain.

3.3. Thermocable-Assisted SAGD Versus Conventional SAGD

The direct reference comparison is shown in Figure 6 and summarized in Table 6. To avoid reducing the comparison to two isolated bars, Figure 6 uses a paired multi-indicator layout that simultaneously reports steam mass used for SOR, oil rate, SOR, downstream measured-depth temperature and the normalized heat-loss index. The comparison is interpreted together with propagated engineering uncertainty in Table 6.

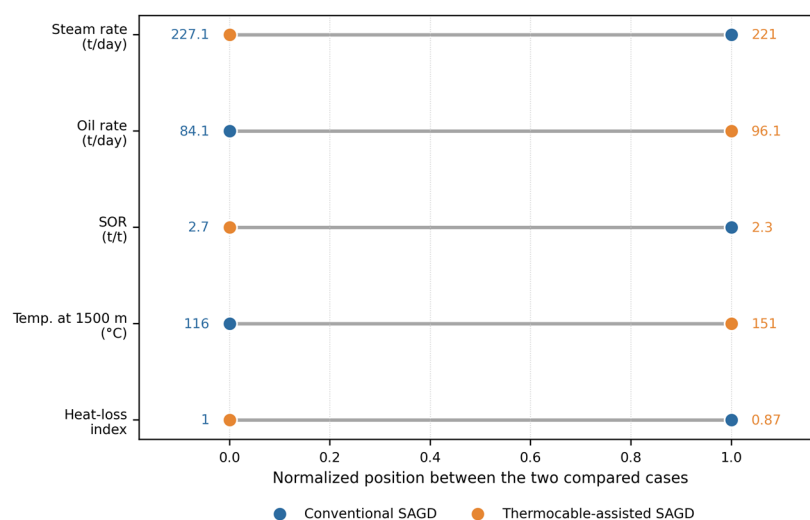


Figure 6. Reference-case paired comparison across production and energy indicators. The connected-point format compares conventional and thermocable-assisted SAGD by effective steam mass used for SOR, oil rate, downstream measured-depth temperature and normalized heat-loss index. The values correspond to the reference-case mass-and-energy consistency calculation rather than to independent long-term field-history measurements; propagated engineering uncertainty is reported in Table 6.

Table 6 reports the quantitative reference-case comparison corresponding to Figure 6 and adds propagated engineering uncertainty. The uncertainty bounds are not interpreted as formal confidence intervals from repeated field trials. They are used to test

whether the main screening differences remain larger than plausible uncertainty in steam mass, oil rate, temperature estimation and normalized heat-loss indexing.

The values in Table 6 confirm that the reported oil-rate increase, SOR reduction and downstream temperature rise are larger than the propagated paired uncertainty used in the screening analysis. The normalized heat-loss-index reduction is also larger than the assigned index uncertainty, although it should be interpreted as a relative indicator rather than as a direct MW-scale loss reduction. The table therefore supports the reference-case comparison while avoiding a claim of formal statistical significance from repeated field trials.

The reference-case comparison supports the central mechanism of this paper: The cable does not simply add bulk heat to the system. It changes where a small amount of heat is supplied and how the downstream temperature field is stabilized. The uncertainty-bounded comparison indicates that the predicted improvement is not explained by small numerical fluctuations within the screening assumptions. However, the values should still be verified by distributed temperature sensing, steam-quality measurements and production-history data in a field pilot.

3.4. Cable-Power Saturation and Longitudinal Temperature Stabilization

Figure 7 examines cable-power response together with marginal production gain and total energy demand. This form is more informative than a single oil-rate curve because cable sizing must account for both incremental production and additional electrical input.

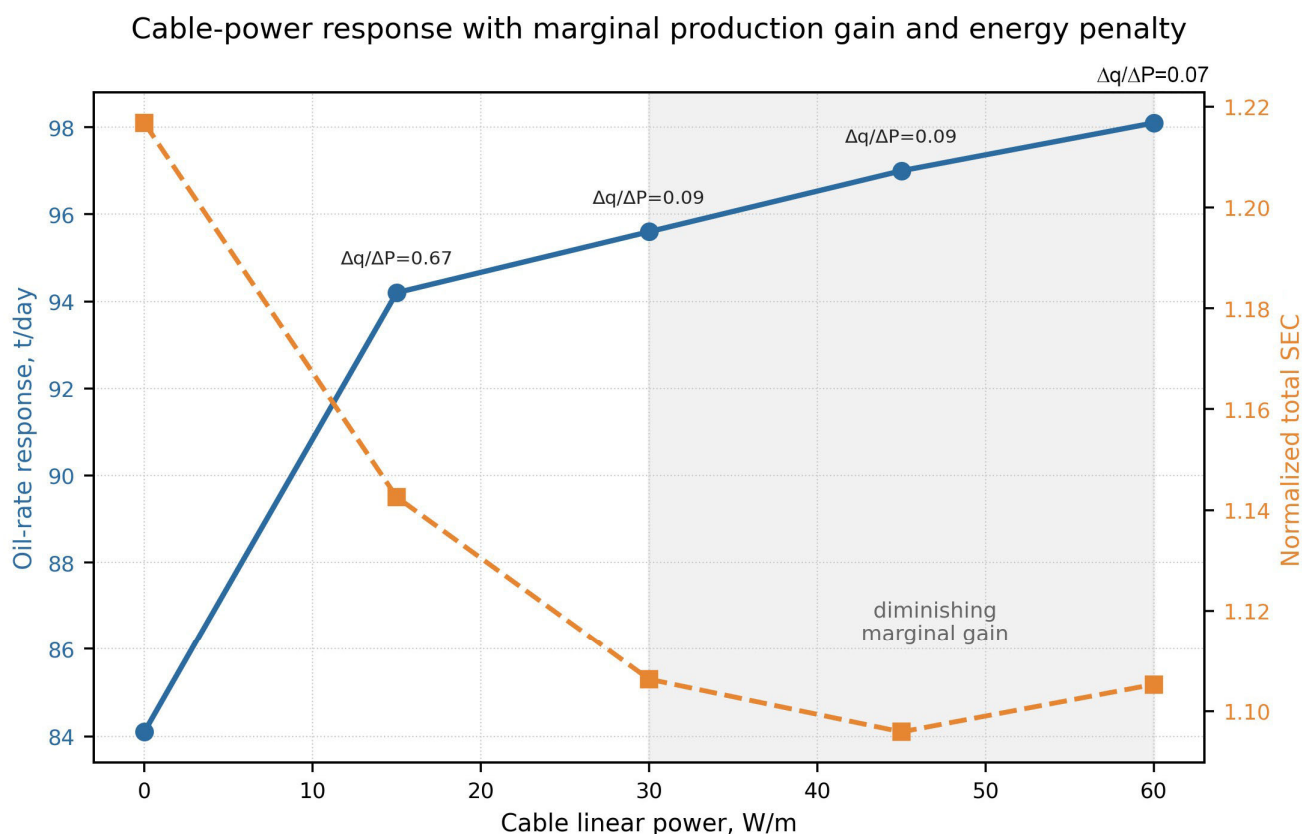


Figure 7. Cable-power response with marginal production gain and total specific-energy indicator. The figure shows that the thermocable effect is beneficial but saturating; after the intermediate-power interval, additional cable power gives a smaller oil-rate increment and must be checked against total energy use. Fixed matrix points are shown as markers; the connecting trends represent model-interpolated responses within the admissible screening domain.

The physical reason for this saturation is visible in the distance-power temperature map in Figure 8. Instead of comparing only two longitudinal profiles, the map shows how the entire horizontal interval responds to cable power. The relevant mechanism is not a large increase in total system heat but a reduction in the length of the downstream interval that remains below the effective viscosity-reduction temperature. Δ

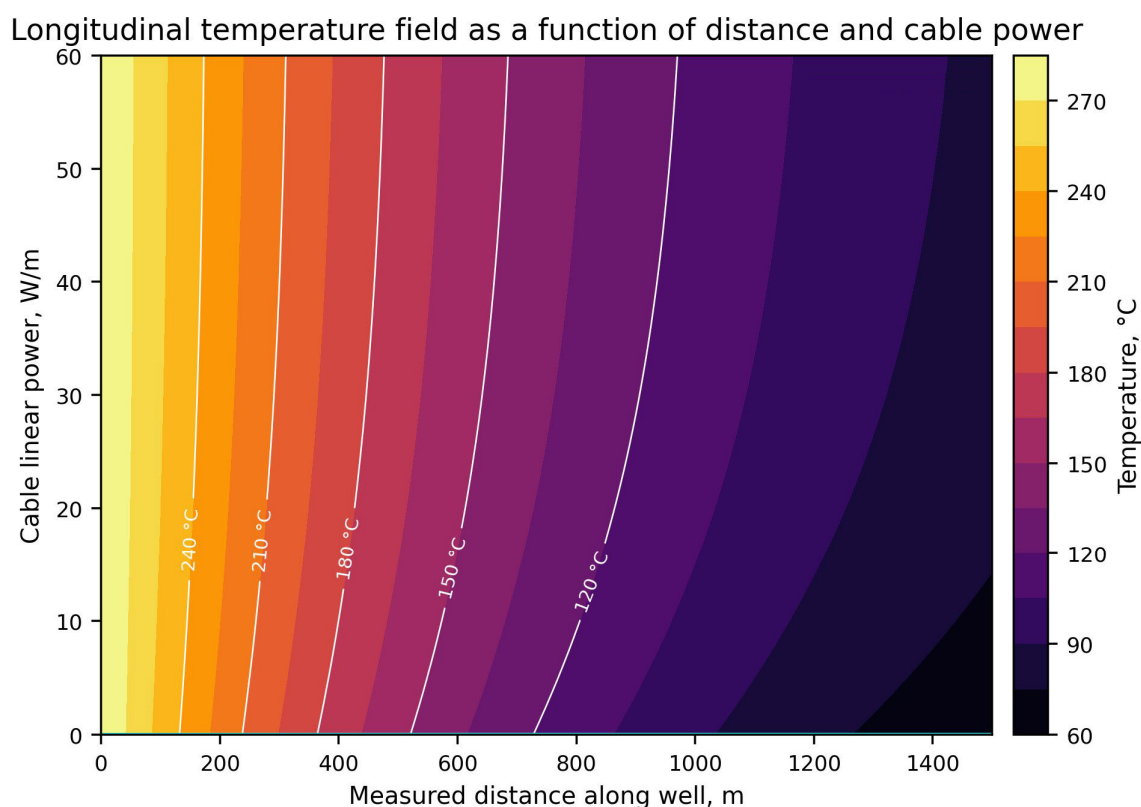


Figure 8. Longitudinal temperature field as a function of measured distance and cable linear power. The map shows how cable power counteracts downstream cooling and extends the interval where temperature remains sufficient for viscosity reduction. Fixed matrix points are shown as markers; the color field is the model-interpolated response within the admissible screening domain.

Using the reference temperature threshold implied by the viscosity-transformation model, thermocable assistance reduced the underheated downstream interval from approximately 280 m in the conventional case to approximately 90–120 m in the 45 W/m cable-assisted case. In the same comparison, the estimated downstream measured-depth temperature increased from about 116 °C to about 151 °C. Therefore, the apparent production leverage is linked to the reduction of a limiting cold interval rather than to the cable heat fraction in the total energy balance.

The spatial chamber-field reconstruction in Figure 9 further illustrates that the cable-supported case produces a more laterally continuous heated zone. This does not replace detailed reservoir simulation, but it provides a useful screening-level visualization of where useful heat is likely to contribute to chamber growth and mobility increase.

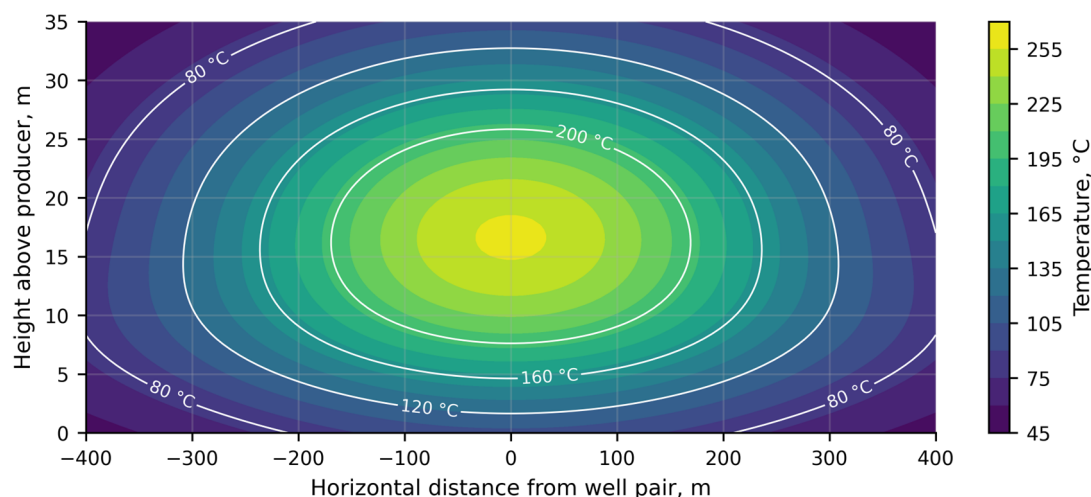


Figure 9. Thermal chamber structure for the reference case. Contours indicate the spatial distribution of the heated region and the transition from high-temperature chamber core to lower-temperature halo. The contour field represents a model-predicted screening response within the admissible domain rather than a direct field-imaging result.

3.5. Depth-Dependent Heat-Loss Compensation

Depth is the main geological factor that increases the practical value of thermocable assistance. Figure 10 therefore presents the result as a heat-loss/productivity phase trajectory rather than as two separate depth curves.

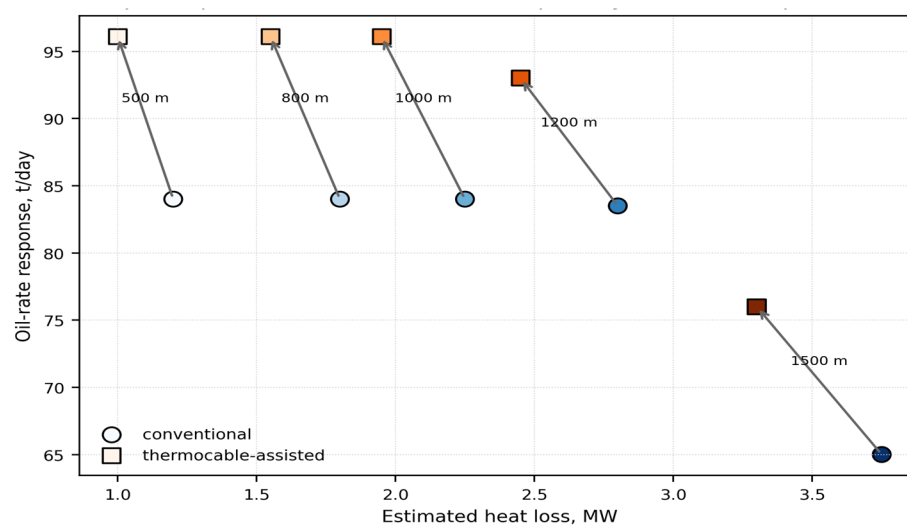


Figure 10. Depth-dependent heat-loss/productivity phase trajectory. Arrows show the shift from conventional SAGD to thermocable-assisted SAGD for each depth class, indicating simultaneous heat-loss reduction and oil-rate stabilization. The plotted shifts correspond to model-predicted screening responses for fixed depth classes within the admissible domain.

Figure 11 combines vertical depth and cable power in a contour benefit map. This representation separates the depth-driven increase in thermocable usefulness from the saturation of the power response.

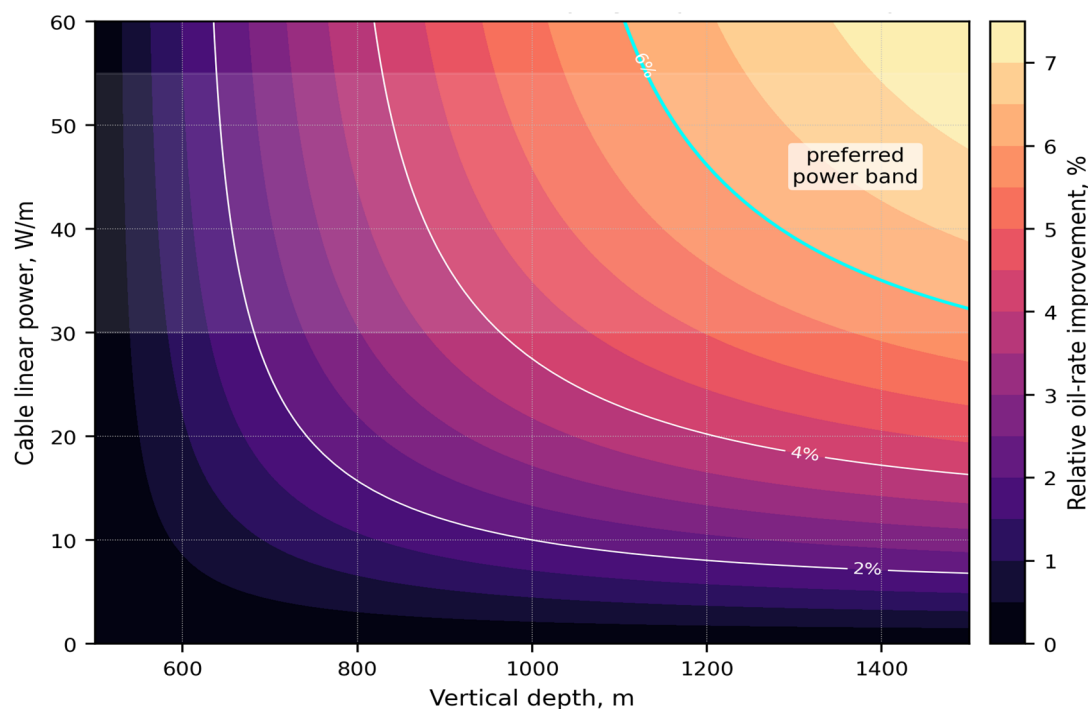


Figure 11. Thermocable relative-benefit map by vertical depth and cable linear power. The contour representation shows that cable assistance becomes more valuable at greater depth but remains subject to power saturation. Fixed matrix points are shown as markers; the color field is the model-interpolated response within the admissible screening domain.

3.6. Sensitivity Ranking, Operating Window and Energy Balance

The sensitivity analysis in Figure 12 was formulated as a joint production-SOR map. This representation is necessary because a parameter that increases oil-rate response can also increase the steam-use penalty, and the two effects should not be judged from a one-dimensional ranking alone. The sensitivity coefficients were calculated by symmetric perturbation around the reference thermocable-assisted case, with all non-perturbed variables fixed at their Tables 3 and 4 reference values.

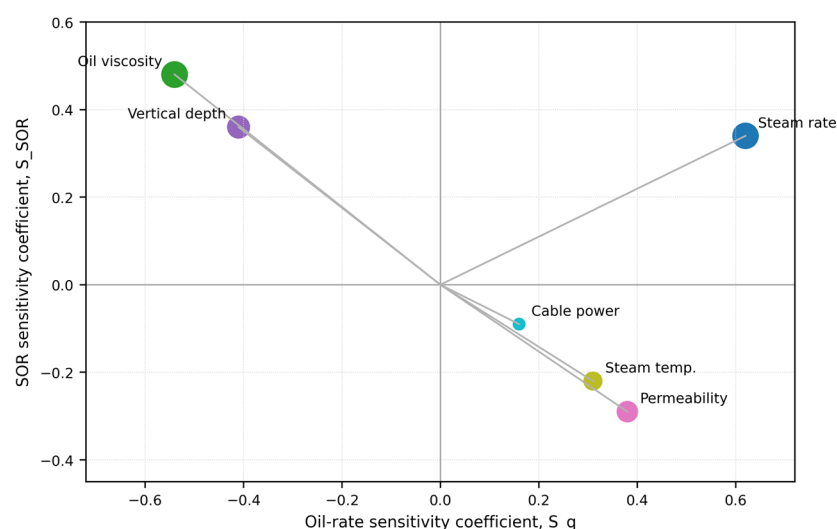


Figure 12. Joint sensitivity map for oil-rate response and SOR response. Each point represents one perturbed variable; the horizontal coordinate shows S_q , the vertical coordinate shows S_{SOR} and marker size reflects the combined magnitude of the local response. The plotted sensitivities are

calculated from $\pm 15\%$ symmetric perturbations around the reference thermocable-assisted case and should be interpreted as local model-based screening indicators.

Figure 12 shows that the governing variables do not act in the same direction with respect to production and steam efficiency. Effective steam mass has the strongest positive effect on oil-rate response, but it also increases the SOR-related penalty, which confirms that steam injection should not be maximized without an energy-efficiency constraint. Initial oil viscosity and vertical depth move the response toward lower production and higher SOR, indicating that fluid mobility and wellbore heat-loss exposure are the main limiting factors in the screening domain. Permeability and steam temperature improve the conversion of delivered heat into gravity drainage, whereas cable linear power produces a smaller but directionally favorable effect by increasing oil-rate response and reducing SOR. Therefore, the sensitivity map supports the interpretation of the thermocable as a secondary but systematic spatial heat-control element rather than as the dominant driver of SAGD performance.

$$S_{q,i} = \frac{(q_i^+ - q_i^-) / q_0}{(x_i^+ - x_i^-) / x_{i,0}}, \quad (36)$$

$$S_{SOR,i} = \frac{(SOR_i^+ - SOR_i^-) / SOR_0}{(x_i^+ - x_i^-) / x_{i,0}}, \quad (37)$$

where $S_{q,i}$ is the local oil-rate sensitivity coefficient for variable x_i ; $S_{SOR,i}$ is the local SOR sensitivity coefficient for variable x_i ; q_i^+, q_i^- are oil-rate responses obtained at positive and negative perturbations of x_i ; SOR_i^+, SOR_i^- are the corresponding SOR values; q_0 and SOR_0 are reference-case outputs; and $x_{i,0}$ is the baseline value of the perturbed variable. Unless constrained by the admissible screening domain, the perturbation amplitude was $\pm 15\%$. The reference thermocable-assisted baseline used for the sensitivity calculation was as follows: depth = 1000 m, initial oil viscosity = 700 mPa·s, permeability = 1000 mD, steam temperature = 260 °C, effective steam mass used for SOR = 221.0 t/day, cable linear power = 45 W/m, oil rate $q_0 = 96.1$ t/day and $SOR_0 = 2.30$ t/t.

Pairwise interactions were evaluated by comparing the two-factor response with the sum of the corresponding one-factor responses. For oil rate, the interaction residual was calculated as

$$I_{q,ij} = \Delta q_{ij} - (\Delta q_i + \Delta q_j), \quad (38)$$

where $I_{q,ij}$ is the pairwise interaction residual for variables x_i and x_j , t/day; Δq_{ij} is the oil-rate change under simultaneous perturbation of x_i and x_j ; and $\Delta q_i, \Delta q_j$ are the corresponding one-factor oil-rate changes. The same logic was applied to SOR. Interactions were interpreted qualitatively as weak when the residual was below 5% of the reference response, moderate at 5–10% and strong above 10%.

Table 7 provides the local one-factor sensitivity coefficients used to support the graphical ranking in Figure 12. The table reports the baseline value, perturbation interval, oil-rate sensitivity, SOR sensitivity and main interaction note for each variable. The separation of S_q and S_{SOR} is necessary because a factor that improves production can simultaneously increase steam-use penalty.

Table 7. Local sensitivity coefficients and interaction notes for oil-rate and SOR response.

Variable	Baseline Value	Perturbation Interval	Oil-Rate Sensitivity S_q	SOR Sensitivity S_{SOR}	Main Interaction Note	Interpretation
Effective steam mass used for SOR	221.0 t/day	±15%	+0.62	+0.34	Interacts with steam temperature and depth	Dominant operational control, but higher steam input can increase steam-use penalty
Initial oil viscosity	700 mPa·s	±15%	−0.54	+0.48	Strong interaction with steam temperature	Dominant fluid-property limitation controlling mobility
Vertical depth	1000 m	±15%	−0.41	+0.36	Strong interaction with cable power	Heat-loss and delivery-penalty driver
Permeability	1000 mD	±15%	+0.38	−0.29	Moderate interaction with viscosity	Controls conversion of heating into gravity drainage
Steam temperature	260 °C	±15%, bounded by 220–300 °C	+0.31	−0.22	Strong interaction with viscosity and steam quality	Supports viscosity reduction and chamber growth
Cable linear power	45 W/m	±15%, bounded by 0–60 W/m	+0.16	−0.09	Strongest in deep or downstream-cooling-limited cases	Secondary global sensitivity but systematic spatial heat-control effect

The sensitivity coefficients in Table 7 support the main design conclusion: cable power is useful, but it is not the primary global control variable. Effective steam mass, oil viscosity and vertical depth dominate the overall response because they define the thermal and filtration regime. Cable linear power has a smaller global sensitivity coefficient, but its interaction with depth indicates that it becomes more relevant when downstream cooling and wellbore heat-loss penalties are stronger.

This result does not contradict the thermocable interpretation. The thermocable is not presented as the dominant energy source or the primary determinant of SAGD performance. It is presented as a targeted auxiliary control that improves the spatial usefulness of heat in thermally disadvantaged intervals. Therefore, cable sizing should be optimized together with steam supply, reservoir depth, oil viscosity and permeability rather than maximized independently.

The operating-window map in Figure 13 translates this sensitivity structure into a practical screening tool. The preferred region combines oil rate above approximately 94 t/day with SOR below approximately 2.45 t/t. This region is not obtained by maximizing steam rate alone; it requires a balanced combination of steam supply and distributed heat support.

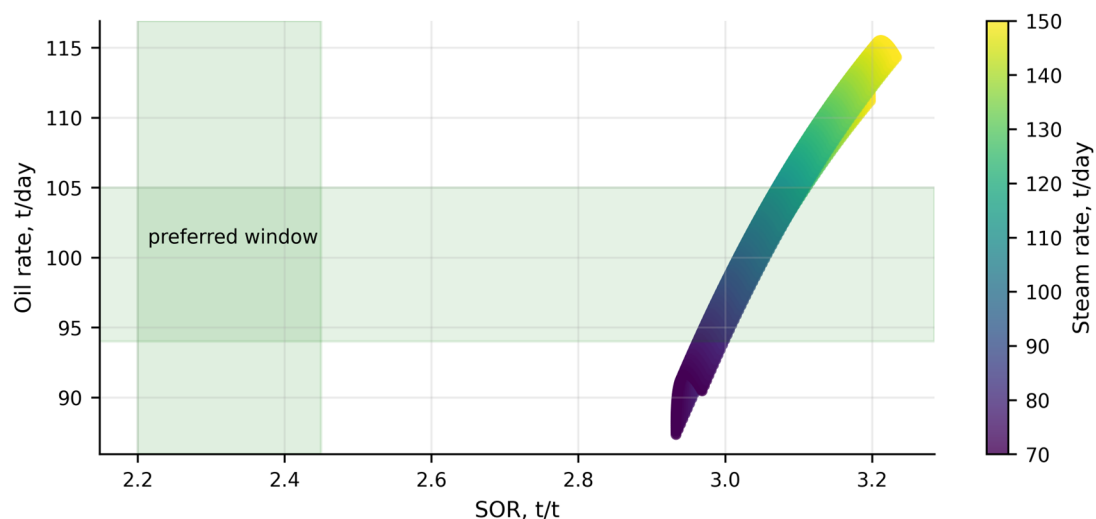


Figure 13. Operating-window map for thermocable-assisted SAGD. The preferred window combines relatively high oil rate with moderate SOR rather than maximizing a single control variable. The preferred region follows the objective and constraints in Equations (31) and (32). Fixed matrix points are shown as markers; the color field is the model-interpolated response within the admissible screening domain.

Because the thermocable consumes electricity, a separate heat-input balance is required. Figure 14 and Table 8 report the reference-case steam-temperature basis, saturated-pressure basis, steam dryness, equivalent enthalpy drop, steam-delivery efficiency and cable heat-utilization coefficient used in the heat-balance calculation. In the reference case, useful cable heat is approximately 0.026 MW, whereas useful steam heat is approximately 5.01 MW in the thermocable-assisted case. This corresponds to a cable-to-useful-steam heat ratio of approximately 0.5%. This value is used only for global energy-scale interpretation. The mechanism of the predicted benefit is evaluated at the local scale through the downstream heat-deficit compensation ratio in Equation (14).

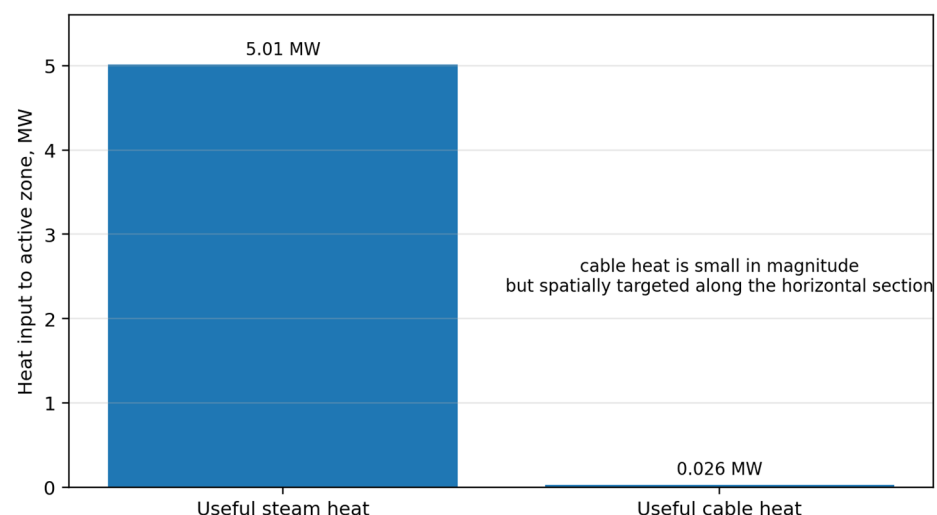


Figure 14. Heat-input balance for the reference case. The global cable-to-useful-steam heat ratio is used only for energy-scale interpretation, whereas the thermocable mechanism is evaluated through local downstream heat-deficit compensation. The values are calculated from the reference-case heat-balance assumptions and are used for scale interpretation.

Table 8 details the heat-input balance used to interpret Figure 14. The table separates useful steam heat, installed cable power, useful cable heat and the cable-to-steam heat

ratio so that the thermocable contribution is not misinterpreted as a dominant bulk heat source. The same table also reports a local downstream compensation interpretation, which is the relevant scale for explaining the predicted temperature and oil-rate response.

Table 8. Approximate heat-input balance for the reference case.

Quantity	Value	Comment
Effective steam mass used for SOR	227.1 t/day conventional; 221.0 t/day thermocable-assisted	Scenario-specific steam masses used consistently with $SOR = \frac{M_{\text{steam}}}{M_{\text{oil}}}$
Mass flow rate	2.63 kg/s conventional; 2.56 kg/s thermocable-assisted	Converted from daily steam mass for heat-balance calculation
Steam-temperature basis	260 °C reference case	Same steam-temperature basis as in Table 3
Steam-pressure basis	Approximately 4.7 MPa	Saturated-steam pressure corresponding to 260 °C
Steam dryness fraction	($x_s = 0.90$) reference value	Sensitivity checked over $x_s = 0.85$ – 0.95
Equivalent steam enthalpy drop	2.8 MJ/kg steam/water properties; sensitivity checked over 2.55–2.85 MJ/kg	Reference screening value based on IAPWS-IF97
Gross steam heat input	7.36 MW conventional; 7.16 MW thermocable-assisted	Calculated as ($m_s \Delta h_s$)
Steam-delivery efficiency	$\eta_s = 0.68$ conventional; $\eta_s = 0.70$ thermocable-assisted	Reference screening coefficients; sensitivity checked over $\eta_s = 0.65$ – 0.72
Useful steam heat	5.00 MW conventional; 5.01 MW thermocable-assisted	Calculated from gross steam heat input and η_s
Cable electrical input	0.0306 MW	45 W/m $\times$ 800 m $\times$ 0.85 active coverage
Cable heat-utilization coefficient	$\eta_c = 0.85$	Reference screening coefficient; sensitivity checked over $\eta_c = 0.75$ – 0.90
Useful cable heat	0.026 MW	Cable electrical input multiplied by η_c
Cable-to-useful-steam heat ratio	$\approx 0.5\%$	Global energy-scale indicator; not used as the main mechanism metric
Estimated downstream measured-depth temperature	116 °C conventional; 151 °C thermocable-assisted	Indicates local thermal stabilization in the downstream interval
Approximate underheated downstream interval	≈ 280 m conventional; ≈ 90 – 120 m thermocable-assisted	Screening estimate based on the effective viscosity-reduction temperature threshold
Local compensation interpretation	Cable contribution is small globally but targeted locally	The thermocable is evaluated against downstream heat deficit, not against total useful steam heat
Total-energy interpretation	SOR improvement is primarily a steam-efficiency and heat-placement effect	Total SEC must include both steam heat and cable electricity

Table 8 reinforces the local-compensation interpretation of thermocable assistance. The useful cable heat is small in absolute terms compared with useful steam heat; therefore, the thermocable contribution is not treated as bulk energy replacement. Its engineering relevance is instead associated with reducing the length and severity of the downstream underheated interval. In this interpretation, the 0.5% global energy ratio and the local thermal effect are not contradictory because they refer to different scales of the heat-transfer problem.

3.7. Cross-Consistency Checks and Three-Dimensional Operating Surfaces

The model was additionally checked through three-dimensional response surfaces. Each surface is linked to the mathematical structure of the formulation and to a specific consistency requirement. The first requirement is that cable-related gains should increase with depth only when the heat-loss penalty is large enough for local compensation to matter. Figure 15 therefore maps relative oil-rate improvement as a function of vertical depth and cable linear power.

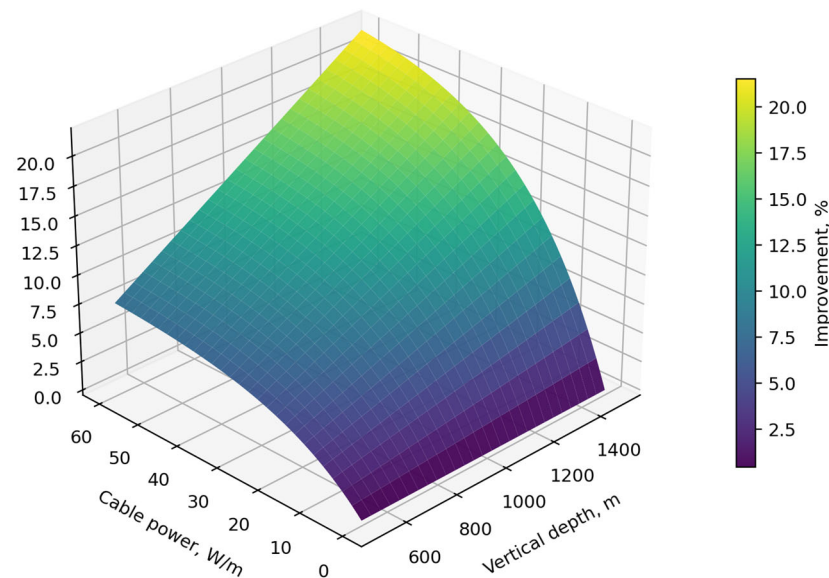


Figure 15. Three-dimensional depth-power response surface. The predicted thermocable benefit increases with depth because wellbore heat-loss penalties become more important, while the power response saturates above approximately 45–60 W/m. The surface represents a model-predicted screening response interpolated between fixed matrix points within the admissible domain.

The second check concerns steam-chamber geometry. Figure 16 visualizes the chamber as a three-dimensional heated body. This representation is linked to Equations (23)–(26): chamber height, width and volume are not independent outputs but geometrically constrained variables. The temperature color scale provides a qualitative indication of the transition from the high-temperature chamber core to the lower-temperature thermal halo.

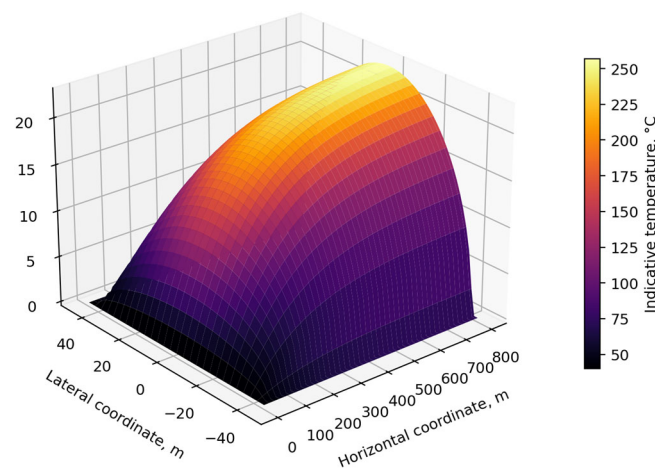


Figure 16. Three-dimensional steam-chamber morphology for the thermocable-assisted reference case. The surface links chamber height, lateral spread and longitudinal growth to the thermal field

and illustrates why spatial heat placement affects drainage geometry. The surface represents a model-predicted screening response interpolated between fixed matrix points within the admissible domain.

The third check concerns total energy performance. Figure 17 uses Equation (28) to map the normalized total SEC over steam rate and cable power. The surface shows that minimizing steam use alone is insufficient; excessive cable power or excessive steam rate can both move the system away from the most energy-efficient region.

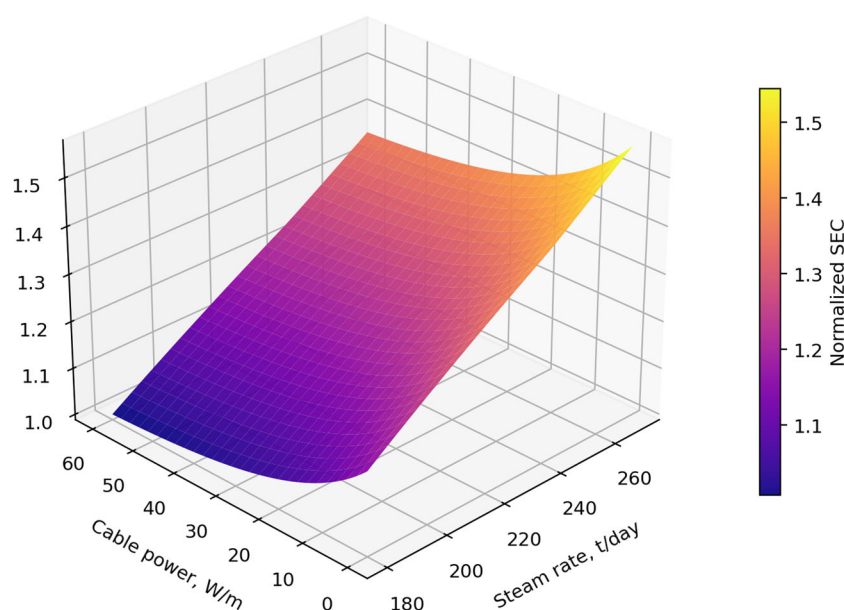


Figure 17. Three-dimensional total specific-energy-consumption surface. The optimal region is located at moderate steam rate and moderate cable power, which supports the operating-window logic rather than single-parameter maximization. The surface represents a model-predicted screening response interpolated between fixed matrix points within the admissible domain.

The final consistency check is the mass-balance relation between steam rate, oil rate and SOR. In the reference case, the conventional operating case uses 227.1 t/day of effective steam for 84.1 t/day of oil, giving $SOR = 2.70$ t/t. The thermocable-assisted operating case uses 221.0 t/day for 96.1 t/day of oil, giving $SOR = 2.30$ t/t. The normalized heat-loss index in Table 6 is therefore not interpreted as a direct MW reduction; dimensional energy quantities are reported separately in Table 8.

4. Discussion

4.1. Physical Interpretation of the Thermocable Effect

The results support a mechanism-based interpretation of thermocable-assisted SAGD. The useful cable heat is small when compared with total useful steam heat; however, the relevant mechanism is local rather than global. The thermocable provides the largest practical value where conventional steam delivery is spatially inefficient: long horizontal intervals, deep reservoirs and downstream regions with strong temperature attenuation. In such cases, a small distributed electrical input can reduce the downstream heat deficit, shorten the underheated interval and increase the portion of the horizontal section that remains above the effective viscosity-reduction temperature. This explains why the predicted oil-rate gain is larger than would be expected from the global cable-to-steam heat ratio alone.

The scale mismatch is therefore resolved by distinguishing two denominators. For the global heat balance, the useful cable heat is compared with useful steam heat, giving a ratio of approximately 0.5%. For the local mechanism, the same cable heat is compared with the downstream heat deficit in the cable-covered interval. The latter comparison is more relevant for viscosity reduction and chamber continuity because oil-rate response is controlled by the coldest limiting section rather than by the average heat input over the whole SAGD system.

The uncertainty analysis should be interpreted conservatively. The oil-rate, SOR, downstream-temperature and normalized heat-loss differences exceed the propagated engineering uncertainty used in the screening calculation, but they do not constitute formal statistical proof from repeated long-term field trials. The role of this analysis is to show that the reported reference-case differences are not smaller than the uncertainty inherent in the reduced-order screening assumptions.

The findings are consistent with the classical SAGD view that production depends on chamber growth and gravity drainage rather than on nominal heat input alone [51–53]. They also align with previous studies of electrical downhole heating, which emphasize start-up acceleration, local heat placement and reduction of cold intervals near the wellbore [54–56].

4.2. Engineering Implications

The engineering implication is that thermocable-assisted SAGD should not be designed by maximizing cable power. Figures 7 and 11 show a saturating response. A technically defensible design should therefore specify a power interval, active coverage and operation duration that improve longitudinal thermal uniformity without producing unnecessary electrical-energy consumption.

The lower global sensitivity of cable power does not contradict the thermocable-assisted SAGD mechanism. Steam mass, viscosity and depth control the dominant energy and flow structure of the process; therefore, they naturally have larger sensitivity coefficients. Cable power is a secondary global variable, but it becomes important when the limiting mechanism is local downstream underheating. In such cases, the thermocable modifies the spatial distribution of useful heat rather than the total heat input. This is why the design conclusion is not to maximize cable power but to optimize it within a bounded operating window.

For pre-field screening, the reduced-order digital-twin prototype can be used in three ways. First, it can identify cases where depth and viscosity make conventional SAGD thermally inefficient. Second, it can estimate whether a modest distributed heat source is sufficient to stabilize the downstream temperature profile. Third, it can define a bounded operating window before a more expensive full-physics thermal-reservoir simulation is launched.

The operating-window maps should therefore be interpreted as a decision-support layer for experimental design. They indicate which combinations of steam rate and cable power deserve pilot testing, which combinations are unlikely to be energy efficient and where additional field measurements would most reduce uncertainty.

A further practical implication concerns instrumentation. If thermocable assistance is deployed in a pilot test, the most informative measurements are not only total oil rate and injected steam mass but also distributed temperature along the producer, steam quality at the injection point, cable current and voltage, pressure response and produced-fluid temperature. These measurements would allow the heat-placement mechanism identified in this study to be tested directly rather than inferred only from aggregate SOR improvement.

4.3. Preliminary Economic Screening and Electricity-Price Boundary

The present work is not a full techno-economic assessment; nevertheless, an economic screening boundary is necessary because thermocable assistance adds electrical-energy consumption to the SAGD process. The economic interpretation should therefore compare the incremental value of additional oil production with the additional electrical cost and the change in steam-generation cost. This screening relation is not intended to replace field-specific economic modeling, but it prevents the thermocable effect from being interpreted only through SOR and oil-rate indicators.

$$\Delta\Pi = p_o\Delta M_o - c_{el}E_{c,el} - c_s\Delta Q_s, \quad (39)$$

where $\Delta\Pi$ is the incremental net value of thermocable assistance over the considered interval, USD or other currency unit; p_o is the net oil value per ton after field-level lifting and handling costs, USD/t; ΔM_o is the incremental oil mass produced due to thermocable assistance, t; c_{el} is the electricity price, USD/MWh; $E_{c,el}$ is the electrical energy consumed by the thermocable over the same interval, MWh; c_s is the steam-generation heat cost, USD/GJ; and ΔQ_s is the change in gross steam heat requirement between the thermocable-assisted and conventional cases, GJ.

In this convention, $\Delta Q_s < 0$ indicates a reduction in gross steam heat demand and therefore improves the incremental economic balance. Conversely, high electricity price or low incremental oil value can make thermocable assistance unattractive even when SOR improves.

$$c_{el}^{BE} = \frac{p_o\Delta M_o - c_s\Delta Q_s}{E_{c,el}}, \quad (40)$$

where c_{el}^{BE} is the break-even electricity price, USD/MWh. Thermocable assistance is economically admissible in the preliminary screening sense when

$$c_{el} < c_{el}^{BE}. \quad (41)$$

Equation (40) should be interpreted as a site-specific screening equation. It does not prescribe a universal electricity-price threshold because p_o, c_s , produced-fluid handling cost, fuel-gas cost, carbon cost, water-treatment cost and electricity tariff vary between projects.

The preliminary economic interpretation is summarized in Table 9. The table separates quantities already calculated in the thermal screening model from site-specific economic inputs that must be supplied by the operator before a field-scale decision can be made.

Table 9. Preliminary economic-screening variables for thermocable-assisted SAGD.

Variable	Unit	Reference or Required Value	Status in This Study	Role in Economic Screening
ΔM_o	t/day	12.0 t/day reference increment	Calculated from reference comparison	Incremental oil mass produced by thermocable assistance
$E_{c,el}$	MWh/day	0.734 MWh/day	Calculated from 0.0306 MW cable electrical input	Additional electrical-energy demand

ΔQ_s	GJ/day	Site-specific; negative if steam heat demand is reduced	Derived from gross steam heat comparison	Change in steam-generation heat requirement
p_o	USD/t	Operator- or scenario-defined	Not fixed universally	Net oil value after field-level costs
c_{el}	USD/MWh	Operator- or tariff-defined	Not fixed universally	Electricity-price input
c_s	USD/GJ	Operator-defined	Not fixed universally	Steam-generation heat-cost input
c_{el}^{BE}	USD/MWh	Calculated from Equation (40)	Scenario output	Break-even electricity price for thermocable assistance
Economic admissibility rule	—	$c_{el} < c_{el}^{BE}$	Screening criterion	Thermocable assistance is economically admissible only below the break-even electricity price

Table 9 shows that the economic feasibility of thermocable-assisted SAGD cannot be inferred from the cable-to-steam heat ratio alone. The relevant economic condition depends on the value of incremental oil production, the cost of electrical energy and the change in steam-generation cost. For this reason, this manuscript reports a break-even electricity-price equation rather than a single universal cost value. A complete techno-economic assessment should additionally include capital cost of the cable system, installation and workover costs, reliability and downtime risk, power-supply constraints, steam-generator fuel cost, produced-water treatment and emissions-related costs.

4.4. Limitations and Validation Pathway

The present model is a reduced-order experimental–analytical tool. It does not replace coupled geomechanical, compositional, or three-phase thermal-reservoir simulation. The reported values should therefore be interpreted as screening-level estimates within the declared operating envelope. Field calibration is required before using the model for operational control. Table 10 summarizes the main methodological, physical and economic limitations of the proposed reduced-order digital-twin prototype. The table is placed in the Discussion because these limitations define how the reported operating window should be interpreted and what validation steps are required before field-scale deployment.

Table 10. Main limitations and required validation steps.

Limitation	Effect on Interpretation	Required Next Step
Reduced-order heat transfer	Does not resolve all completion details, local heat-transfer resistances, multi-phase thermal coupling, or transient wellbore-reservoir interaction.	Benchmark against detailed thermal-reservoir simulators and coupled wellbore heat-transfer models.
Parametric steam-chamber model	Approximates chamber height, width and active volume using smooth reduced-order growth functions. Local heterogeneity, shale barriers, steam override and conformance effects are not resolved.	Compare chamber-growth predictions with CMG/ECLIPSE-type thermal simulations, laboratory analogues, or monitored SAGD pilot data.
Thermocable heat placement	Uses an effective distributed heat-source term and a local compensation ratio rather than a fully coupled electrical–thermal cable model.	Validate against distributed temperature sensing, cable current and voltage logs and measured downhole temperature profiles.
Steam-property and heat-delivery assumptions	Steam pressure, dryness fraction, equivalent enthalpy drop and delivery efficiency are	Replace reference values with measured steam quality, pressure, temperature, separator data and site-specific steam-generator performance.

	treated as reference screening parameters with sensitivity intervals.	
No long-term field-history match	Current results are screening outputs and should not be interpreted as a calibrated long-term production forecast.	Calibrate against field production history, steam injection records, pressure response, water cut, produced-fluid temperature and SOR trends.
Uncertainty interpretation	Reported uncertainty bounds are propagated engineering uncertainties, not formal confidence intervals from repeated long-term field trials.	Add repeated pilot observations, instrument-specific error estimates and statistical confidence intervals when field data become available.
Operating-domain limitation	Quantitative results are valid only within the declared admissible screening domain for depth, viscosity, permeability, steam temperature, steam quality, cable power and heating time.	Recalibrate the model before applying it to other reservoir depths, fluid properties, completion geometries, steam qualities, or long-term operating regimes.
Cable-power saturation	Cable power is treated as a bounded auxiliary heat-control variable. The model does not justify unlimited cable-power increase.	Optimize cable power jointly with steam rate, depth, viscosity, permeability, electricity cost and thermal-response measurements.
Preliminary economic interpretation	Provides only a break-even electricity-price screening relation and does not include capital cost, workover cost, reliability risk, downtime, field-specific tariffs, or emissions penalties.	Extend the model to a full techno-economic assessment using operator-specific electricity price, steam-generation cost, oil netback, cable CAPEX/OPEX, downtime risk and emissions-related costs.
Digital-twin prototype status	The framework is executable and decision-oriented, but it is not a real-time synchronized field digital twin with automatic data assimilation.	Develop a calibrated field implementation with online data assimilation from temperature, pressure, steam-quality, cable-power and production measurements.

The validation pathway in Table 10 prevents overextension of the model. The present results are suitable for experimental screening and candidate-regime selection, whereas operational control requires calibration against field temperature profiles, steam-quality measurements, pressure response, production histories and detailed reservoir characterization. Economic deployment additionally requires a site-specific break-even electricity-price calculation, including oil netback, electricity tariff, steam-generation cost, cable CAPEX/OPEX, downtime risk and emissions-related costs.

5. Conclusions

A reduced-order digital-twin prototype for thermocable-assisted SAGD was developed for screening deep heavy-oil reservoirs under coupled heat-transfer, chamber-growth and steam-efficiency constraints. The model provides a unified interpretation of oil rate, SOR, temperature distribution, normalized heat-loss response and depth-dependent thermal penalties. It is intended for feasibility assessment and preliminary operating-window selection rather than for direct operational control without detailed field calibration.

For the reference case, thermocable assistance increased the oil-rate response from 84.1 ± 2.5 to 96.1 ± 2.9 t/day and reduced SOR from 2.70 ± 0.09 to 2.30 ± 0.08 t/t under propagated engineering uncertainty. The useful cable heat was approximately 0.026 MW, corresponding to about 0.5% of useful steam heat, so the effect cannot be interpreted as bulk energy replacement. The predicted improvement is instead attributed to local downstream heat-deficit compensation, reduction of the underheated interval and longitudinal temperature-profile stabilization.

Within the reference screening interpretation, the bulk-energy contribution of the thermocable accounts for less than 1% of the useful heat input, whereas the dominant

explanatory mechanism is spatial: local temperature stabilization and reduction of the downstream underheated interval. This distinction is essential for avoiding overstatement of the thermocable as an energy source.

Under the reference-case assumptions, steam temperature improved oil rate and reduced SOR up to an approximate plateau interval of 250–270 °C. This interval is specific to the reference viscosity, permeability, depth and steam-quality assumptions and should not be treated as a universal SAGD threshold. Increasing oil viscosity sharply reduced production and increased SOR, while increasing permeability improved the conversion of heat into gravity drainage.

Cable power showed a non-linear saturating effect and a smaller global sensitivity coefficient than steam mass, oil viscosity and vertical depth. This does not weaken the thermocable interpretation because its role is not to dominate the total energy balance but to correct local downstream underheating. The main practical design implication is that cable power should be optimized within an admissible operating window instead of being maximized. The largest relative benefit occurs in deeper or thermally disadvantaged reservoirs where conventional SAGD is penalized by stronger wellbore heat losses and downstream temperature attenuation.

The proposed reduced-order digital-twin prototype is suitable for preliminary engineering screening, comparative regime assessment and selection of candidate operating windows. Its quantitative outputs are strictly valid only within the declared admissible screening domain and should not be extrapolated to other reservoir depths, viscosities, permeabilities, steam qualities, cable configurations, or long-term field conditions without recalibration.

An additional preliminary economic-screening relation was introduced to define the break-even electricity price for thermocable assistance. This relation shows that the method is economically admissible only when the value of incremental oil production and any reduction in steam-generation cost exceed the added electrical-energy cost. Therefore, thermocable-assisted SAGD should be evaluated jointly by oil-rate response, SOR, total specific energy consumption and site-specific electricity and steam-generation costs.

The next development stage should include benchmarking against detailed thermal-reservoir simulators and calibration using field temperature profiles, steam-quality measurements, pressure response, oil rate, water cut and production-history data. Overall, thermocable-assisted SAGD is most defensible when it is used to improve spatial heat utilization in thermally disadvantaged intervals, not when it is treated as a substitute for steam energy.

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Abbreviations

The table below lists the abbreviations used in the manuscript. This table is included to improve readability because the article combines SAGD terminology, heat-transfer notation and energy-efficiency indicators.

Abbreviation	Definition
EOR	Enhanced oil recovery
SAGD	Steam-assisted gravity drainage
SOR	Steam–oil ratio
SEC	Specific energy consumption
VIT	Vacuum-insulated tubing

References

1. Gates, I.D.; Larter, S.R. Energy efficiency and emissions intensity of SAGD. *Fuel* **2014**, *115*, 706–713. <https://doi.org/10.1016/j.fuel.2013.07.073>.
2. Guo, K.; Li, H.; Yu, Z. In-situ heavy and extra-heavy oil recovery: A review. *Fuel* **2016**, *185*, 886–902. <https://doi.org/10.1016/j.fuel.2016.08.047>.
3. Dong, X.; Liu, H.; Chen, Z.; Wu, K.; Lu, N.; Zhang, Q. Enhanced oil recovery techniques for heavy oil and oilsands reservoirs after steam injection. *Appl. Energy* **2019**, *239*, 1190–1211. <https://doi.org/10.1016/j.apenergy.2019.01.244>.
4. Bera, A.; Babadagli, T. Status of electromagnetic heating for enhanced heavy oil/bitumen recovery and future prospects: A review. *Appl. Energy* **2015**, *151*, 206–226. <https://doi.org/10.1016/j.apenergy.2015.04.031>.
5. Cui, G.; Liu, T.; Xie, J.; Rong, G.; Yang, L. A review of SAGD technology development and its possible application potential on thin-layer super-heavy oil reservoirs. *Geosci. Front.* **2022**, *13*, 101382. <https://doi.org/10.1016/j.gsf.2022.101382>.
6. Pratama, R.A.; Babadagli, T. A review of the mechanics of heavy-oil recovery by steam injection with chemical additives. *J. Pet. Sci. Eng.* **2022**, *208*, 109717. <https://doi.org/10.1016/j.petrol.2021.109717>.
7. Zhao, D.W.; Wang, J.; Gates, I.D. Thermal recovery strategies for thin heavy oil reservoirs. *Fuel* **2014**, *117*, 431–441. <https://doi.org/10.1016/j.fuel.2013.09.023>.
8. Prats, M. The heat efficiency of thermal recovery processes. *J. Pet. Technol.* **1969**, *21*, 323–332. <https://doi.org/10.2118/2211-PA>.
9. Wang, L.; Liu, H.; Pang, Z.; Lv, X. Overall heat transfer coefficient with considering thermal contact resistance in thermal recovery wells. *Int. J. Heat Mass Transf.* **2016**, *103*, 486–500. <https://doi.org/10.1016/j.ijheatmasstransfer.2016.07.050>.
10. Nian, Y.L.; Cheng, W.L. Insights into heat transport for thermal oil recovery. *J. Pet. Sci. Eng.* **2017**, *151*, 507–521. <https://doi.org/10.1016/j.petrol.2017.01.026>.
11. Banerjee, S.; Hascakir, B. Flow control devices in SAGD completion design: Enhanced heavy oil/bitumen recovery through improved thermal efficiency. *J. Pet. Sci. Eng.* **2018**, *169*, 297–308. <https://doi.org/10.1016/j.petrol.2018.05.064>.
12. Guo, J.; Zan, C.; Ma, D.; Shi, L. Oil production rate predictions for steam assisted gravity drainage based on high-pressure experiments. *Sci. China Technol. Sci.* **2013**, *56*, 324–334. <https://doi.org/10.1007/s11431-012-5096-y>.
13. Ni, J.; Zhou, X.; Yuan, Q.; Lu, X.; Zeng, F.; Wu, K. Numerical simulation study on steam-assisted gravity drainage performance in a heavy oil reservoir with a bottom water zone. *Energies* **2017**, *10*, 1999. <https://doi.org/10.3390/en10121999>.
14. Ji, D.; Xu, J.; Lyu, X.; Li, Z.; Zhan, J. Numerical modeling of the steam chamber ramp-up phase in steam-assisted gravity drainage. *Energies* **2022**, *15*, 2933. <https://doi.org/10.3390/en15082933>.
15. Zhang, L.; Du, D.; Zhang, Y.; Liu, X.; Fu, J.; Li, Y.; Ren, J. Steam cavity expansion model for steam flooding in deep heavy oil reservoirs. *Energies* **2022**, *15*, 4816. <https://doi.org/10.3390/en15134816>.
16. Xie, H.; Zhang, S.; Wu, G.; Li, W. Study on thermal chamber expansion of VH-SAGD process using CO₂-inducing effect for heavy oil reservoirs. *Processes* **2024**, *12*, 2260. <https://doi.org/10.3390/pr12102260>.
17. Queipo, N.V.; Goicochea, J.V.; Pintos, S. Surrogate modeling-based optimization of SAGD processes. *J. Pet. Sci. Eng.* **2002**, *35*, 83–96. [https://doi.org/10.1016/S0920-4105\(02\)00167-5](https://doi.org/10.1016/S0920-4105(02)00167-5).
18. Kong, X.; Liu, Y.; Xue, L.; Li, G.; Zhu, D. A hybrid oil production prediction model based on artificial intelligence technology. *Energies* **2023**, *16*, 1027. <https://doi.org/10.3390/en16031027>.
19. Fan, D.; Lai, S.; Sun, H.; Yang, Y.; Yang, C.; Fan, N.; Wang, M. Review of machine learning methods for steady-state capacity and transient production forecasting in oil and gas reservoirs. *Energies* **2025**, *18*, 842. <https://doi.org/10.3390/en18040842>.

20. Raissi, M.; Perdikaris, P.; Karniadakis, G.E. Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. *J. Comput. Phys.* **2019**, *378*, 686–707. <https://doi.org/10.1016/j.jcp.2018.10.045>.
21. Karniadakis, G.E.; Kevrekidis, I.G.; Lu, L.; Perdikaris, P.; Wang, S.; Yang, L. Physics-informed machine learning. *Nat. Rev. Phys.* **2021**, *3*, 422–440. <https://doi.org/10.1038/s42254-021-00314-5>.
22. Fuller, A.; Fan, Z.; Day, C.; Barlow, C. Digital twin: Enabling technologies, challenges and open research. *IEEE Access* **2020**, *8*, 108952–108971. <https://doi.org/10.1109/ACCESS.2020.2998358>.
23. Kritzinger, W.; Karner, M.; Traar, G.; Henjes, J.; Sihn, W. Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine* **2018**, *51*, 1016–1022. <https://doi.org/10.1016/j.ifacol.2018.08.474>.
24. Jones, D.; Snider, C.; Nassehi, A.; Yon, J.; Hicks, B. Characterising the digital twin: A systematic literature review. *CIRP J. Manuf. Sci. Technol.* **2020**, *29*, 36–52. <https://doi.org/10.1016/j.cirpj.2020.02.002>.
25. Rasheed, A.; San, O.; Kvamsdal, T. Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE Access* **2020**, *8*, 21980–22012. <https://doi.org/10.1109/ACCESS.2020.2970143>.
26. Malozyomov, B.V.; Martyushev, N.V.; Kukartsev, V.V.; Tynchenko, V.S.; Bukhtoyarov, V.V.; Wu, X.; Tynchenko, Y.A.; Kukartsev, V.A. Overview of methods for enhanced oil recovery from conventional and unconventional reservoirs. *Energies* **2023**, *16*, 4907. <https://doi.org/10.3390/en16134907>.
27. Zaurbekov, K.S.; Zaurbekov, S.A.; Sladkovsky, A.V.; Balgayev, D.Y. Hydrodynamic simulation of the steam-assisted gravity drainage method for different reservoir thicknesses using Eclipse. *News Natl. Acad. Sci. Repub. Kazakhstan Ser. Geol. Tech. Sci.* **2023**, *3*, 60–69. <https://doi.org/10.32014/2023.2518-170X.299>.
28. Butler, R.M.; Stephens, D.J. The gravity drainage of steam-heated heavy oil to parallel horizontal wells. *J. Can. Pet. Technol.* **1981**, *20*, 90–96. <https://doi.org/10.2118/81-02-07>.
29. Butler, R.M. *Thermal Recovery of Oil and Bitumen*; Prentice Hall: Englewood Cliffs, NJ, USA, 1991.
30. Prats, M. *Thermal Recovery*; SPE Monograph Series; Society of Petroleum Engineers: Richardson, TX, USA, 1986.
31. Green, D.W.; Willhite, G.P. *Enhanced Oil Recovery*; SPE Textbook Series; Society of Petroleum Engineers: Richardson, TX, USA, 1998.
32. Yelemessov, K.; Baskanbayeva, D.; Sabirova, L.; Martyushev, N.V.; Malozyomov, B.V.; Zhanar, T.; Golik, V.I. Algorithmic optimal control of screw compressors for energy-efficient operation in smart power systems. *Algorithms* **2025**, *18*, 583. <https://doi.org/10.3390/a18090583>.
33. Lake, L.W.; Johns, R.T.; Rossen, W.R.; Pope, G.A. *Fundamentals of Enhanced Oil Recovery*; Society of Petroleum Engineers: Richardson, TX, USA, 2014.
34. Aziz, K.; Settari, A. *Petroleum Reservoir Simulation*; Applied Science Publishers: London, UK, 1979.
35. Ertekin, T.; Abou-Kassem, J.H.; King, G.R. *Basic Applied Reservoir Simulation*; SPE Textbook Series; Society of Petroleum Engineers: Richardson, TX, USA, 2001.
36. Chen, Z.; Huan, G.; Ma, Y. *Computational Methods for Multiphase Flows in Porous Media*; SIAM: Philadelphia, PA, USA, 2006. <https://doi.org/10.1137/1.9780898718942>.
37. Boberg, T.C. *Thermal Methods of Oil Recovery*; John Wiley & Sons: New York, NY, USA, 1988.
38. Wu, Y.; Yang, M.; Wang, J.; Liu, X.; Li, H.; Zhang, Y. Strategies of SAGD start-up by downhole electrical heating. *Energies* **2022**, *15*, 5135. <https://doi.org/10.3390/en15145135>.
39. Bybee, K. Electrical downhole heaters for Faja heavy-oil reservoirs. *J. Pet. Technol.* **2009**, *61*, 77–79. <https://doi.org/10.2118/0309-0077-JPT>.
40. Malozyomov, B.V.; Martyushev, N.V.; Voitovich, E.V.; Kononenko, R.V.; Konyukhov, V.Y.; Tynchenko, V.; Kukartsev, V.A.; Tynchenko, Y.A. Designing the optimal configuration of a small power system for autonomous power supply of weather station equipment. *Energies* **2023**, *16*, 5046. <https://doi.org/10.3390/en16135046>.
41. Bottazzi, F.; Repetto, C.; Tita, E.; Galli, G.; Maugeri, G. Downhole electrical heating for heavy oil enhanced recovery: A successful application in Offshore Congo. In Proceedings of the International Petroleum Technology Conference, Beijing, China, 26–28 March 2013; IPTC-16858-MS. <https://doi.org/10.3997/2214-4609-pdb.350.iptc16858>.
42. Malozyomov, B.V.; Golik, V.I.; Brigida, V.; Kukartsev, V.V.; Tynchenko, Y.A.; Boyko, A.A.; Tynchenko, S.V. Substantiation of drilling parameters for undermined drainage boreholes for increasing methane production from unconventional coal-gas collectors. *Energies* **2023**, *16*, 4276. <https://doi.org/10.3390/en16114276>.

43. Penny, S.; Karanikas, J.M.; Barnett, J.; Harley, G.; Hartwell, C.; Waddell, T. Field case studies of downhole electric heating in two horizontal Alberta heavy oil wells. In Proceedings of the SPE Annual Technical Conference and Exhibition, Calgary, AB, Canada, 30 September–2 October 2019; SPE-196187-MS. <https://doi.org/10.2118/196187-MS>.
44. Karanikas, J.M.; Pastor, G.; Penny, S. Downhole electric heating of heavy-oil wells. *CT&F Cienc. Tecnol. Futuro* **2020**, *10*, 61–72. <https://doi.org/10.29047/01225383.273>.
45. Sandberg, C.; Hale, A.; Kovscek, A.R. History and applications of resistance electrical heaters in downhole oil field applications. In Proceedings of the SPE Western Regional & AAPG Pacific Section Meeting, Monterey, CA, USA, 19–25 April 2013; SPE-165323-MS. <https://doi.org/10.2118/165323-MS>.
46. Glaessgen, E.; Stargel, D. The digital twin paradigm for future NASA and U.S. Air Force vehicles. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, HI, USA, 23–26 April 2012; AIAA 2012-1818. <https://doi.org/10.2514/6.2012-1818>.
47. Boschert, S.; Rosen, R. Digital twin-The simulation aspect. In *Mechatronic Futures: Challenges and Solutions for Mechatronic Systems and Their Designers*; Hehenberger, P., Bradley, D., Eds.; Springer: Cham, Switzerland, 2016; pp. 59–74. https://doi.org/10.1007/978-3-319-32156-1_5.
48. Kaliyev, B.; Myrzakhetov, B.; Mauletbekova, B.; Akhymbayeva, B.; Mashatayeva, G.; Merkiyayev, Y.; Golik, V.I.; Malozyomov, B.V. Energy-efficient and reliable hydrodynamic separation of spent drilling fluids: Experiments, modeling, and process stability. *Energies* **2026**, *19*, 1659. <https://doi.org/10.3390/en19071659>.
49. Nussipali, R.; Martyushev, N.V.; Malozyomov, B.V.; Konyukhov, V.Y.; Oparina, T.A.; Romanova, V.V.; Kononenko, R.V. Combined power generating complex and energy storage system. *Electricity* **2024**, *5*, 931–946. <https://doi.org/10.3390/electricity5040047>.
50. Hastie, T.; Tibshirani, R.; Friedman, J. *The Elements of Statistical Learning: Data Mining, Inference, and Prediction*, 2nd ed.; Springer: New York, NY, USA, 2009. <https://doi.org/10.1007/978-0-387-84858-7>.
51. James, G.; Witten, D.; Hastie, T.; Tibshirani, R. *An Introduction to Statistical Learning: With Applications in R*, 2nd ed.; Springer: New York, NY, USA, 2021. <https://doi.org/10.1007/978-1-0716-1418-1>.
52. Forrester, A.I.J.; Sobester, A.; Keane, A.J. *Engineering Design via Surrogate Modelling: A Practical Guide*; John Wiley & Sons: Chichester, UK, 2008. <https://doi.org/10.1002/9780470770801>.
53. Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M.; Tarantola, S. *Global Sensitivity Analysis: The Primer*; John Wiley & Sons: Chichester, UK, 2008. <https://doi.org/10.1002/9780470725184>.
54. Deb, K. *Multi-Objective Optimization Using Evolutionary Algorithms*; Wiley: New York, NY, USA, 2001.
55. Zaurbekov, K.; Zaurbekov, S.; Malozyomov, B.V.; Martyushev, N.V. Physically oriented SAGD profitability model for high-viscosity oil fields. *Energies* **2026**, *19*, 2021. <https://doi.org/10.3390/en19092021>.
56. Agzamov, A.; Efendiyev, G.; Moldabayeva, G.Z.; Syzdykov, A.; Suleimenova, R.; Tuzelbayeva, S.; Zaurbekov, K. On the Degree of Influence of Waterflooding on the Oil Recovery Factor from Productive Formations of High-Viscosity Reservoirs Represented by Terrigenous Reservoirs. *Complex Use of Mineral Resources* **2023**, *326*, 50–58. <https://doi.org/10.31643/2023/6445.28>.

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