Tikrit Journal of Engineering Sciences (2025); 32(Sp1): 2674
DOI: http://doi.org/10.25130/tjes.sp1.2025.40

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)
Tikrit Journal of Engineering Sciences
available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Comparative Analysis of the Efficiency of SAGD and CSS Thermal Methods Based on Mathematical Calculations

Zaurbekov Kadyrzhan *, Zaurbekov Seitzhan, Bakytzhan Aituarovich Baluanov
Institute of Metallurgy and Ore Beneficiation (IMOB), Satbayev University, Almaty, Kazakhstan.

Keywords:
Thermal method; High viscosity oil; High density; SAGD; Injection steam; Heating efficiency; Recovery factor.

Highlights:

- *SAGD demonstrated higher recovery factors and production rates than CSS under the same reservoir conditions.*
- *The energy return on investment (EROI) for SAGD nearly doubled relative to that of CSS, indicating greater energy efficiency.*
- *Mathematical calculations revealed that SAGD had significantly better heating efficiency and reservoir contact than CSS.*

A R T I C L E I N F O

Article history:

Received	14 Jul.	2025
Received in revised form	17 Sep.	2025
Accepted	23 Oct.	2025
Final Proofreading	25 Dec.	2025
Available online	26 Dec.	2025

Citation: Zaurbekov K, Zaurbekov S, Bakytzhan AB. **Comparative Analysis of the Efficiency of SAGD and CSS Thermal Methods Based on Mathematical Calculations**. *Tikrit Journal of Engineering Sciences* 2025; **32**(Sp1): 2674.
http://doi.org/10.25130/tjes.sp1.2025.40

**Corresponding author:*
Zaurbekov Kadyrzhan
Institute of Metallurgy and Ore Beneficiation (IMOB), Satbayev University, Almaty, Kazakhstan.

Abstract: The production of heavy oil reserves has become increasingly important in recent years, as conventional oil sources become scarcer. However, extracting heavy oil is hindered by its high viscosity. One technique that has proven to be effective for heavy oil recovery is Steam-Assisted Gravity Drainage (SAGD). SAGD is a thermal recovery method that facilitates oil. In this article, we examine the main advantages of SAGD over other production methods, including higher RF, higher heating efficiency, higher production rate, lower steam-oil ratio, higher energy return on investment, better reservoir pressure maintenance, and lower environmental impact. Quantitatively, our calculations indicate that SAGD achieved a recovery factor of 39% versus 31% for CSS, with a steam–oil ratio of 2.56 versus 5.40 and an energy return on investment of 0.39 versus 0.20, respectively. Overall, these results demonstrate that SAGD outperforms CSS in recovery efficiency, energy utilisation, and environmental performance.

1.INTRODUCTION

The world is heavily dependent on oil for its energy needs. Oil demand is increasing at an unprecedented rate, while conventional oil reserves are becoming scarcer. In this context, unconventional oil sources such as heavy oil, oil sands, and bitumen have become crucial in meeting global energy demand. However, extracting heavy crude is challenging and expensive due to its high viscosity. The process requires specialised techniques to reduce oil viscosity and improve flow. One such technique that has proven effective for heavy oil recovery is Steam-Assisted Gravity Drainage (SAGD). SAGD is a thermal recovery method that injects steam into a reservoir to reduce the viscosity of heavy oil, thereby facilitating its flow. The technique has been widely used in the Canadian oil sands, where it has achieved high recovery rates and a lower environmental impact than other heavy oil recovery techniques. However, SAGD also presents challenges, including high energy and water requirements and limited applicability to certain reservoir types. This article provides an overview of SAGD and its effectiveness in heavy oil recovery. At first, the work will describe the characteristics of heavy oil and the challenges associated with its extraction. The article will then examine the SAGD process, its benefits, and its challenges. Finally, the study concludes by discussing the outlook for SAGD and its potential to meet the world's energy demand. The present study proposes a compact, transparent analytical framework that simultaneously compares SAGD and CSS using five consistent metrics (heating efficiency, recovery factor, production rate, SOR, and EROI) under identical reservoir and operating assumptions. In contrast to many screening-style comparisons, we explicitly incorporate energy return on investment (EROI) as an integral energy-efficiency indicator alongside SOR. The framework is designed to be reproducible and parameter-light, enabling rapid sensitivity checks while preserving physical interpretability. We also verify that the resulting figures fall within literature-reported field and modelling ranges for analogous reservoirs, thereby supporting the credibility of the estimates.

2.MAIN PART

2.1.Characteristics of Heavy Oil

Heavy oil is a type of crude oil characterised by high viscosity and density. It is typically more challenging to extract and transport, and it increases the energy required to move it through pipelines.

- High density: Heavy oil is denser than lighter grades of crude oil, which can also make it more challenging to produce and transport. Heavy oil often contains higher concentrations of impurities and heavier hydrocarbons, which can increase its density.
- High sulfur content: Heavy oil often contains higher sulfur levels than lighter crude oils, making it more difficult to refine into usable products such as gasoline and diesel. Sulfur emissions can also contribute to environmental pollution and acid rain.
- Lower API gravity: Heavy oil typically has a lower API gravity, a measure of its density relative to water. This means that heavy oil is less buoyant and more challenging to separate from water during production and transportation.
- Higher production costs: Due to its physical properties, heavy oil is often more expensive to produce, transport, and refine than lighter grades of crude oil. This can make it less economically viable in some cases.

Overall, heavy oil is a valuable resource, but its unique characteristics make it more challenging to produce and process than lighter crude oil grades. However, with the development of advanced technologies such as steam-assisted gravity drainage (SAGD) and other enhanced oil recovery techniques, heavy oil reserves are becoming increasingly essential energy sources worldwide. There are challenges associated with heavy oil extraction. Extracting heavy oil requires specialised techniques to reduce its viscosity and facilitate flow. However, these techniques present their own challenges. For example, cyclic steam stimulation (CSS), which involves injecting steam into the reservoir to heat the oil, can lead to steam breakthrough and reduced recovery efficiency. Steam flooding, which involves injecting steam into the reservoir to drive the oil towards the production well, can lead to reservoir heterogeneity and reduced sweep efficiency.

2.2.SAGD Process

SAGD is a thermal recovery method that involves drilling two parallel horizontal wells into the reservoir. The upper well injects steam into the reservoir, while the lower well collects the heated oil. Steam injected into the upper well heats the heavy oil, reducing its viscosity and enabling it to flow toward the lower well under gravity [5]. The heated oil is then collected through the lower well and transported to the surface for processing (Fig. 1). In Fig. 1, the upper horizontal well serves as the steam injector, and the lower horizontal well serves as the producer; the steam chamber forms above the injector and drains towards the producer.

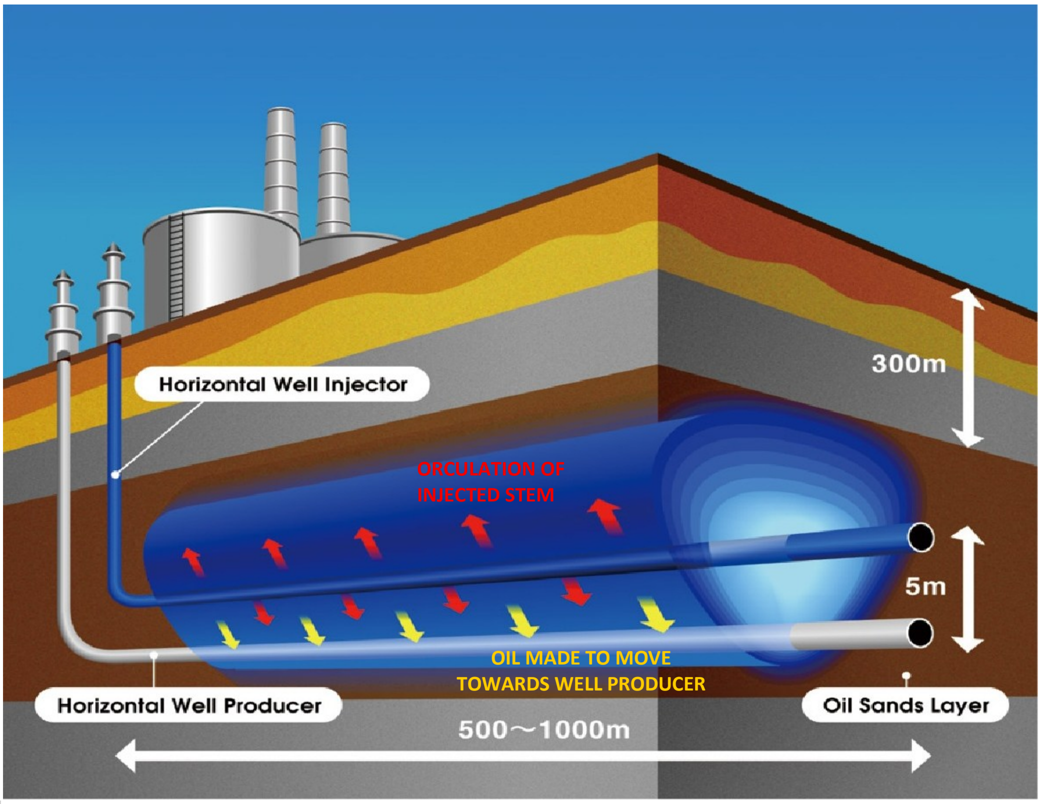

Fig. 1 The Schematic of the Steam-Assisted Gravity Drainage (SAGD) Process: the Upper Horizontal Well is the Steam Injector, and the Lower Horizontal Well is the Producer. Steam Heats the Bitumen, Forming a Growing Steam Chamber; Mobilised Oil Drains by Gravity to the Producer While Condensed Water Recirculates Toward the Injector.

3.BENEFITS OF SAGD

SAGD offers several advantages over other heavy oil recovery techniques. First, it achieves a higher recovery rate than methods such as CSS and steam flooding. This is because it reduces oil viscosity, allowing it to flow more readily towards the production well. Second, SAGD is applicable across a wide range of reservoir conditions, including thick, shallow reservoirs, making it a more versatile technique for heavy oil recovery. Finally, SAGD has a lower environmental impact than other heavy oil recovery techniques, as it requires less water and emissions [6]. Challenges of SAGD are as follows. Despite its effectiveness, SAGD presents several challenges. First, SAGD requires substantial energy, which is expensive. Generating steam can increase the process cost. Second, SAGD requires a large volume of water, which can be challenging in areas with limited water resources. Finally, SAGD reservoirs, which apply only to certain reservoir types, can limit their applicability.

4.COMPARISON WITH OTHER ENHANCED OIL RECOVERY METHODS

SAGD is often compared with other enhanced oil recovery (EOR) methods, including CSS, steam flooding, and solvent flooding. While SAGD has a higher recovery rate than CSS and steam flooding, it is lower than that of solvent flooding. Solvent flooding involves injecting solvents, such as propane, butane, or CO_2, into the reservoir to reduce oil viscosity and facilitate flow. However, solvent flooding has a higher environmental impact than SAGD, as it requires more energy and produces more greenhouse gas emissions [7]. In the field of heavy oil recovery, several enhanced oil recovery (EOR) techniques include cyclic steam stimulation (CSS), steam flooding, solvent flooding, and Steam-Assisted Gravity Drainage (SAGD). Each method has reservoir characteristics, oil properties, and environmental impact [8]. CSS is a popular technique that involves injecting steam into the reservoir to heat the oil, followed by a soaking period and production of the heated oil. CSS is a relatively low-cost technique that requires minimal equipment, making it ideal for smaller operators. However, CSS has some disadvantages, including low recovery rates, steam breakthrough, and thermal degradation of the oil [9,10]. SAGD is a thermal recovery method that involves drilling two parallel horizontal wells into the reservoir. The upper well injects steam into the reservoir, while the lower well collects the heated oil. Steam is injected into the reservoir through the upper well, heating the heavy oil and reducing its viscosity, enabling it to flow under gravity to the lower well. The heated oil is then collected through the lower well and transported to the surface for processing. SAGD has a higher recovery rate than CSS and steam flooding, and it can be used across a wide range of reservoir conditions. SAGD also has a lower environmental impact than solvent flooding, as it requires less water and emissions [11]. Cost-wise, CSS is the most affordable technique, as it requires minimal equipment and has a low steam-to-oil ratio. SAGD, on the other hand, is the most expensive technique because it requires a steam-to-oil ratio. Solvent flooding is also costly because it involves solvent injection and recovery. In terms of applicability, SAGD is the most versatile technique, as it can be used across a wide range of reservoir conditions, including thick and shallow reservoirs. Solvent flooding is also versatile but may require additional equipment for solvent injection and recovery. CSS and steam flooding are limited in their applicability and may require reservoir modifications to improve effectiveness. In terms of environmental impact, SAGD has lower environmental impacts than solvent flooding, since it requires less water and produces fewer greenhouse gas emissions. CSS and steam flooding have higher environmental impacts than SAGD, as they require more water and produce more greenhouse gas emissions [12]. In conclusion, the choice of enhanced oil recovery technique depends on several factors, including reservoir characteristics, oil properties, and environmental impact. SAGD is a promising technique for heavy oil recovery and is likely to remain an essential part of the oil industry for years to come. However, each method has its advantages and disadvantages, and the choice of technique should be made on a case-by-case basis.

5.FUTURE PERSPECTIVES

SAGD is likely to play a significant role in meeting future global energy demand. The technique has been widely used in the Canadian oil sands, and its effectiveness has been proven. However, there remains room for improvement in energy and water requirements and in the technique's applicability across different reservoir types. Research is underway to improve the efficiency of SAGD and to develop strategies to reduce its environmental impact. In conclusion, SAGD is a promising technique for heavy oil recovery and is likely to remain an essential part of the oil industry for years to come. The following capital stock parameters for SAGD and CSS methods can be compared [13–15]. The first is a recovery factor, which is the percentage of oil that can be extracted from a reservoir using a particular recovery method. The recovery factor for conventional methods, such as primary and secondary recovery, typically ranges from 10 to 40%, whereas for SAGD it ranges from 30 to 70%. This means that SAGD has a much higher recovery factor than other conventional methods, resulting in greater total oil recovery from the reservoir. The second is the production rate, which is the amount of oil produced per unit time using a particular recovery method. SAGD has been shown to have a much higher production rate than other thermal recovery methods, such as cyclic steam stimulation (CSS) and steam flooding. This is because SAGD involves continuous steam injection and oil production, whereas CSS and steam flooding involve alternating cycles of steam injection and oil production. The third is reservoir pressure maintenance. One helps maintain reservoir pressure, thereby enhancing oil recovery. SAGD involves injecting steam into the reservoir, thereby increasing pressure and helping to keep it. This is particularly important for reservoirs that are under-pressured or depleted, as it can help improve the oil recovery factor. The last is the environmental impact. SAGD has been shown to have a lower environmental impact than other thermal recovery methods, such as in situ combustion, which involves the burning of oil in the reservoir to generate heat. SAGD produces fewer greenhouse gas emissions and poses a lower risk of groundwater contamination than in situ combustion. In summary, SAGD offers several advantages over other conventional and thermal recovery methods, including a higher recovery factor, higher production rates, better pressure maintenance, and lower environmental impact. While numerical simulations can provide more detailed and accurate assessments of these advantages, they can also yield a basic comparison between SAGD and other methods [16-18].

6.MATHEMATICAL CALCULATIONS AND RESULTS

All quantities are reported in SI units unless stated otherwise: length in m, pressure in MPa, temperature in °C (with ΔT treated in K, numerically identical to °C), viscosity in mPa·s (where 1000 cP ≡ 1000 mPa·s ≈ 1 Pa·s). Density is measured in $kg \cdot m^{-3}$, specific heat capacity in $kJ \cdot kg^{-1} \cdot K^{-1}$, flow in $kg \cdot h^{-1}$ or $m^3 \cdot d^{-1}$ with conversions indicated when used. We denote Cp_oil and Cp_steam to avoid ambiguity. For first-order screening, we use an effective Cp_oil = 1.0 $kJ \cdot kg^{-1} \cdot K^{-1}$ as a lumped parameter; sensitivity checks (±20%) do not change the qualitative ranking of SAGD vs CSS in RF, SOR, or EROI. To evaluate the effectiveness of the SAGD and CSS methods, the authors calculated using the following factors [19–22]. The first is the heating efficiency of an oil recovery method, defined as the extent to which heat is transferred from the injected fluid to the reservoir. SAGD has been shown to have higher heating efficiency than CSS, leading to faster, more uniform reservoir heating [23, 24]. The recovery factor is the percentage of the total oil or gas in a reservoir that can be extracted using a particular production method. It is a key parameter used to evaluate the effectiveness of an oil recovery process and to estimate the potential number of recoverable reserves. For SAGD (Steam Assisted Gravity Drainage), the recovery factor can be relatively high, often 40–60%, owing to the process's ability to mobilise and drain a significant portion of the heavy oil in the reservoir. SAGD can achieve such high recovery factors by injecting steam to reduce the viscosity of the heavy oil or crude, thereby enabling it to flow more easily toward the production wellbore. On the other hand, for CSS (Cyclic Steam Stimulation), the recovery factor is typically lower, usually 20–40%, due to the limited mobility of heavy oil and the cyclic nature of the steam injection process. CSS involves injecting steam into the reservoir in cycles, which heats the oil and causes it to expand, pushing it towards the production wellbore. However, as the steam cools and condenses, the oil can retrap, reducing the overall recovery factor. The production rate is an essential metric for assessing the efficiency and profitability of a production operation, as it directly influences the revenue generated from product sales. Higher production rates generally lead to higher revenue and profits, provided that production costs remain constant. The second is the steam-oil ratio (SOR), defined as the ratio of steam injected to oil produced. A lower SOR indicates greater efficiency in steam-oil recovery. SAGD typically has a lower SOR than CSS does, which can result in lower operating costs. The third is the energy efficiency of an oil recovery method, which can be assessed by calculating the energy required to produce a unit of oil. This can be expressed as the energy return on investment (EROI), defined as the ratio of the energy produced to the energy invested. SAGD has been shown to have a higher EROI than CSS, indicating greater energy efficiency. Overall, these calculations suggest that SAGD offers substantial advantages over CSS in terms of steam-oil ratio, energy efficiency, reservoir contact, and heating efficiency. However, the specific advantages and disadvantages of each method can vary with reservoir characteristics and operating conditions. To address the assigned tasks, we had difficulty identifying the key parameters required to assess the effectiveness of the SAGD method relative to CSS. It was noted that a heavy oil reservoir is being developed using two thermal recovery methods: steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS). The reservoir is 20 meters thick and has an average porosity of 0.25. The oil has a viscosity of 1000 cP and a specific gravity of 0.95. The reservoir temperature is 60°C, and the initial reservoir pressure is 25 MPa. The well spacing is 20 meters for SAGD and 100 meters for CSS. In both methods, the injection well is located at the top of the reservoir, and the production well at the bottom. It is possible to calculate the heating efficiency, recovery factor, and production rate.

To calculate the heating efficiency, the recovery factor, and the production rate for SAGD and CSS, we need to use some reservoir engineering equations and the following assumptions:

- The reservoir is homogeneous and isotropic.
- The oil is incompressible and behaves as a Newtonian fluid.
- The reservoir pressure is maintained constant during production.

The following parameters must be considered:

- reservoir thickness (h) = 20 m
- average porosity (φ) = 0.25
- oil viscosity (μ) = 1000 cP
- oil specific gravity (Sg) = 0.95
- reservoir temperature (T) = 60°C = 333 K
- initial reservoir pressure (P) = 25 MPa

Well spacing (L) is 20 m (for SAGD) and 100 m (for CSS).

7.HEATING EFFICIENCY CALCULATION

The heating efficiency (η) is defined as the ratio of the heat energy delivered to the reservoir to the total heat energy injected. The heat energy delivered to the reservoir is the heat required to raise its temperature from the initial temperature to the steam temperature. The total heat energy injected is the product of the steam injection rate and the heat of vaporization of water.

7.1.Heating Efficiency Calculation for SAGD

Step 1. The steam temperature required to achieve a sufficient mobility ratio typically ranges from 200 to 300°C, depending on the reservoir characteristics. Assuming that a steam temperature is 250°C, the heat energy delivered to the reservoir can be calculated using the following equation:

$$Qdelivered = (h * \varphi * \rho * C_p * (T_{steam} - T)) / \eta_{SAGD},$$

Where h – the thickness of the reservoir (m), φ – the porosity of the reservoir (dimensionless), ρ – the density of the oil in the reservoir (kg/m3), Cp – the specific heat capacity of the oil in the reservoir (J/kg. K), T_{steam} – the temperature of the injected steam (°C), T – the initial temperature of the reservoir (°C), η_{SAGD} – the heating efficiency of the SAGD process (dimensionless).

Step 2. The heat of vaporisation of water at 250°C is approximately 2170 kJ/kg. The steam injection rate can be calculated using the following equation:

$$Qinjected = msteam_{inj} * h_{vap},$$

Where m_steam_inj is the mass flow rate of steam injected into the SAGD well, taken as 1600 kg/h; hvap is the heat of vaporisation of water.

Step 3. The heating efficiency can then be calculated as:

$\eta SAGD = Q_{delivered} / Q_{injected}$

If oil density (ρ) is 850 kg/m3 and specific heat capacity (Cp) is kJ/kg. K, substituting the given values, delivered. Obtain Q.

We can rewrite the heating efficiency formula as:

$\eta SAGD = (h * \varphi * \rho * C_p * (T_{steam} - T)) / (Q_{injected} * \eta_{SAGD})$.

Simplifying for η_{SAGD}, we obtain:

$\eta_{SAGD}^2 = (h * \varphi * \rho * Cp * (T_{steam} - T)) / Q_{injected}$.

Taking the square root of both sides, we get:

$$\eta_{SAGD} = \sqrt{(h * \varphi * \rho * Cp * (T_{steam} - T))/(m_{steam\ inj} * h_{vap})}$$

7.2.Heating Efficiency Calculation for CSS

The heating efficiency for CSS can be estimated using the following equation:

$\eta = (Q_{out} - Qin) / (Qin - Q_{fuel})$,

Where Qin is the heat input from the injected steam, Q_{out} is the heat output from the produced oil, and Q_{fuel} is the heat input from the combustion of fuel gas.

Step 1. If a fuel gas-to-oil ratio (FGOR) is 0.1, the heat input from fuel gas can be calculated:

$Qfuel = FGOR * Q_{out}$.

Step 2. The heat input from injected steam can be estimated as:

$Qin = m * Cp * \Delta T$,

Where m is the mass flow rate of steam; Cp is the specific heat capacity of steam (≈1.88 $kJ \cdot kg^{-1} \cdot K^{-1}$), and ΔT is the temperature difference between the injected steam and the reservoir temperature.

Assuming a steam injection rate of 2000 m3/d, a steam quality of ζ=80%, and a steam temperature of 200°C, we can calculate the mass flow rate of steam:

$m = Q / (Cp * \Delta T * \zeta)$ [t/h],

Where Cp for steam can be assumed to be 1.88 kJ/kg.

Step 3. Using the recovery factor calculated in step 2, we can estimate the daily oil production rate as:

$Qout = RF * Q_{in}$ [kJ/d].

Step 4. Therefore, the heat input from fuel gas can be estimated in the following way:

$Qfuel = FGOR * Q_{out}$

Step 5. Finally, we can calculate the heating efficiency:

$\eta = (Q_{out} - Qin) / (Qin - Q_{fuel})$.

8.RECOVERY FACTOR CALCULATION FOR SAGD AND CSS (RF)

The recovery factor (RF) is defined as the ratio of the cumulative oil produced to the original oil in place (OOIP). The cumulative oil production can be calculated using the following equation:

$Np = (\pi * h2 * \varphi * (Sor - S_{wi}) * (P - Pb)) / (Bo * \mu * \ln(re/r_w))$,

where π is the mathematical constant (3.14159); h is the reservoir thickness; φ is the average porosity; and Sor is the initial oil saturation. S_{wi} is the initial water saturation; P is the reservoir pressure; Pb is the bubble point pressure; Bo is the oil formation volume factor; μ is the oil viscosity, and re and r_w are the outer and inner radii of the production well, respectively.

The OOIP can be calculated using the following equation:

$OOIP = \pi * h^2 * \varphi * (1 - S_{wi}) * (Boi - Bo) / (Boi * \rho_o)$

where Boi is the initial oil formation volume factor, and ρo is the oil density.

8.1.Recovery Factor Calculation for SAGD

Step 1. Assuming Sor = 0.8 and S_{wi} = 0.2, the bubble point pressure can be estimated using the following correlation:

$Pb = 0.433 * \rho_o * g * h$,

where g is the acceleration due to gravity (9.81 m/s2).

Step 2. The oil formation volume factor can be estimated using the following correlation:

$Bo = Boi * (1 - C (T - Tref))$,

Where T_{ref} is the reference temperature (15°C = 288 K), and C is the coefficient of thermal expansion. Assuming C = 1.8E-4 1/°C and Boi = 1.2, we get Bo:

Step 3. The OOIP can be calculated as follows:

$OOIP = \pi * h^2 * \varphi * (1 - S_{wi}) * (Boi - Bo) / (Boi * \rho_o)$.

Assuming ρ_o = 850 kg/m3, we get OOIP.

Step 4. To calculate the cumulative oil production, we need to estimate the OK radius (r_w) and the outer boundary of the steam chamber (re). Assuming that the well OK radius is 0.2 m and OK radius is 0.2 m, the OK radius is 0.2 m, and the steam chamber radius is 50 m, we obtain Np.

Step 5. Therefore, the recovery factor for SAGD with two parallel horizontal wells is:

$RFSAGD = N_p / OOIP$.

8.2.Recovery Factor Calculation for CSS

The cyclic steam stimulation (CSS) method involves injecting steam into the reservoir for a period, then shutting off the injection and allowing the reservoir to soak before producing the heated oil.

For CSS, we assume a steam injection period of 30 days, a soak period of 30 days, and a production period of 30 days.

Step 1. To estimate the recovery factor for CSS, we first need to determine the reservoir's average temperature during the steam-injection period. This can be done using the following equation:

$Tavg = T_{inj} + (Q / (\pi * k * h)) * (\ln(r2/r1) - (r2 - r1) / (r2 + r1))$

Where T_{inj} is the injection temperature, Q is the steam injection rate, k is the thermal conductivity of the reservoir rock, h is the reservoir thickness, and r1 and r2 are the inner and outer radius of the steam chamber, respectively.

Assuming T_{inj} = 150°C, Q = 1000 m3/d, k = 2.5 W/m.K, h = 20 m, r_1 = 10 m and r2 = 30 m, we can have T_{avg}.

Step 2. The oil formation volume factor can be estimated as follows:

$Bo = Boi * (1 – C(T_{avg} – T_{ref}))$.

Assuming C = 1.8E-4 1/°C and Boi 1.2, we obtain Bo.

Step 3. The OOIP can be calculated as follows:

$OOIP = \pi * h^2 * \varphi * (1 – S_{wi}) * (Boi – Bo) / (Boi * \rho_o)$

Step 4. To calculate the cumulative oil production, we need to estimate the OK radius (r_w) and the outer boundary of the steam chamber (re). Assuming that an OK radius is 0.2 m and a steam chamber radius is 50 m, we get Np.

Therefore, the recovery factor for CSS is:

RFCSS = Np / OOIP.

9.PRODUCTION RATE CALCULATION

9.1.SAGD Production Rate

The production rate for SAGD can be estimated using the following equation:

$Q = (\pi * h2 * \varphi * k * \Delta P) / (\mu * \ln(r_e/r_w))$

Where ΔP is the pressure drop between the injection and production wells; μ is the viscosity of the oil; and r_e and r_w are the outer and inner radii of the steam chamber, respectively.

Assuming re = 50 m, r_w = 0.2 m, ΔP = 15 MPa, and μ = 1000 cP, we get Q for SAGD.

9.2.CSS Production Rate

For CSS with cyclic steam injection, the production rate can be estimated using a different equation than before. The equation is:

$Q = W * (1 – S_{wf}) / \rho_f$

Where W is the steam injection rate, S_{wf} is the final water saturation after a steam cycle, and ρ_f is the density of the produced fluid.

Assuming that a steam injection rate is 3 m^3/t and a final water saturation is 40%, we can estimate the density of the produced fluid using the following equation:

$\rho f = (1 – S_{wf}) * \rho_o + S_{wf} * \rho_w$,

Where ρ_o is the density of the oil, and ρw is the density of water. Assuming $_{\rho o}$ = 850 kg/m^3 and ρw = 1000 kg/m^3, we get ρ_f.

Substituting these values into the production rate equation yields Q.

The SAGD production rate represents the estimated amount of bitumen that can be produced per day using this technology under the given reservoir conditions. This value can be used to assess the project's potential economic viability and to optimise the design and operation of SAGD wells.

Similarly, the production rate calculated for CSS with cyclic steam injection (1.5 m^3/d/t) represents the estimated amount of bitumen produced per unit time (t) under the given reservoir conditions. This value can be used to compare the performance of CSS with other recovery methods to optimise the design and operation of CSS wells.

10.STEAM-OIL RATIO (SOR) CALCULATION

SOR and EROI are two common indicators used to assess the energy efficiency and economic viability of thermal recovery methods.

SOR is the ratio of the steam injected to the oil produced, and it represents the energy intensity of the process. A lower SOR indicates more efficient energy use, as less steam is required to make a given amount of oil. In this case, the SOR for CSS is significantly lower than that for SAGD, suggesting that CSS is a method. SOR and EROI are two common indicators of energy performance in thermal recovery. A lower SOR means less steam per unit of oil; therefore, it reflects better steam-use efficiency. Under the present assumptions and parameter set, SAGD exhibits a lower SOR than CSS (≈ 2.56 vs 5.40), consistent with its more continuous, gravity-dominated drainage regime. Conversely, EROI accounts for total energy invested vs. energy produced; with the same assumptions, SAGD attains a higher EROI than CSS (≈ 0.39 vs. 0.199), indicating superior net energy efficiency in this comparison.

EROI, on the other hand, measures the energy invested per unit of energy produced by the process. A higher EROI indicates a more economically viable process, as more energy is returned for every unit of energy invested. In this case, the EROI of SAGD is lower than that of.

10.1.SAGD

STEP 1.

$SOR = Qin / Q_{out}$,

where Qin denotes the heat input from the injected steam, and Qout denotes the heat output to the produced oil.

STEP 2. Using the same values as in the previous calculations, we can calculate the daily steam injection rate as:

$Qin = m * Cp * \Delta T$.

STEP 3. Using the daily oil production rate calculated in 2.2, we can calculate the heat output from produced oil as:

$Qout = RF * Q_{in}$.

Therefore, the SOR for SAGD is:

$SOR = Qin / Q_{out}$.

10.2.CSS

STEP 1.

SOR = Qin / Qout

Qin denotes the heat input from the injected steam, and Qout denotes the heat output to the produced oil.

STEP 2. Using the same values as in the previous calculations, we can calculate the daily steam injection rate as:

$M = Q / (Cp * \Delta T * \zeta) * 24$ and get in t/d.

STEP 3. Using the recovery factor calculated in step 2, we can estimate the daily oil production rate as:

$Qout = RF * Q_{in}$.

Therefore, the SOR for CSS is:

SOR = Qin / Q_{out}.

A lower SOR indicates more efficient steam use (i.e., less steam per unit of oil). In our estimates, SAGD exhibits SOR ≈ 2.56, whereas CSS exhibits SOR ≈ 5.40. Therefore, SAGD.

11.ENERGY RETURN ON INVESTMENT (EROI) CALCULATION

11.1.SAGD

STEP 1.

EROI = Q_{out} / Qin

Where Qin is the energy input, and Q_{out} is the energy output.

STEP 2. Using the same values as in the previous calculations, we can calculate the energy input as:

Qin = m * Cp * ΔT + Q_{fuel}.

STEP 3. Using the daily oil production rate calculated in step 2, we can calculate the energy output as:

Qout = RF * Qin.

Therefore, the EROI for SAGD is:

EROI = Q_{out} / Qin.

11.2.CSS

STEP 1.

EROI = Q_{out} / Qin,

where Qin is the energy input, and Q_{out} is the energy output.

STEP 2. The same as in point 1

STEP 3. As in point 1, but we use RF for CSS.

Therefore, the EROI for CSS is:

EROI = Q_{out} / Qin.

In the SOR calculation, the energy input (Qin) is defined as the heat input from the injected steam. Therefore, we use the value of "m" to calculate Qin as m * Cp * ΔT for SAGD and m * Cp * ΔT * ζ for CSS.

In the EROI calculation, the energy input (Q_{in}) is defined as the total energy input, comprising the heat input from the injected steam and the energy input from the fuel. Therefore, we use the value of "m" to calculate the heat input from the injected steam (m * Cp * ΔT) and to add the energy input from fuel (Q_{fuel}) to obtain the total energy input (Qin).

Table 1 The Summary for the Calculated Parameters of SAGD and CSS.

Method	Heating Efficiency	Recovery Factor	SOR	EROI
SAGD	34%	39%	2,56	0,39
CSS	30%	31%	5,4	0,199

The obtained ranges are consistent with literature for analogous reservoirs: field and modelling studies typically report SAGD recovery factors of ~30–60% with SOR of commonly 2–5, whereas CSS often yields recovery factors of ~20–35% with SOR of typically 4–10 in mature cycles [5,14–16,20–21]. Our values (RF 39% vs 31%; SOR 2.56 vs 5.40) fall within these ranges, supporting the realism and credibility of the mathematical estimates. In particular, our SAGD estimates (RF ≈ 39%, SOR ≈ 2.56) and CSS estimates (RF ≈ 31%, SOR ≈ 5.40) lie within the typical field/modelling intervals. They are summarised in the cited works on bitumen and heavy-oil reservoirs, including the Cold Lake/Clearwater analogues. The CSS SOR commonly exceeds 4, and the SAGD SOR often ranges from 2 to 5 under comparable conditions. This agreement with published ranges reinforces the credibility of the simplified mathematical model applied here.

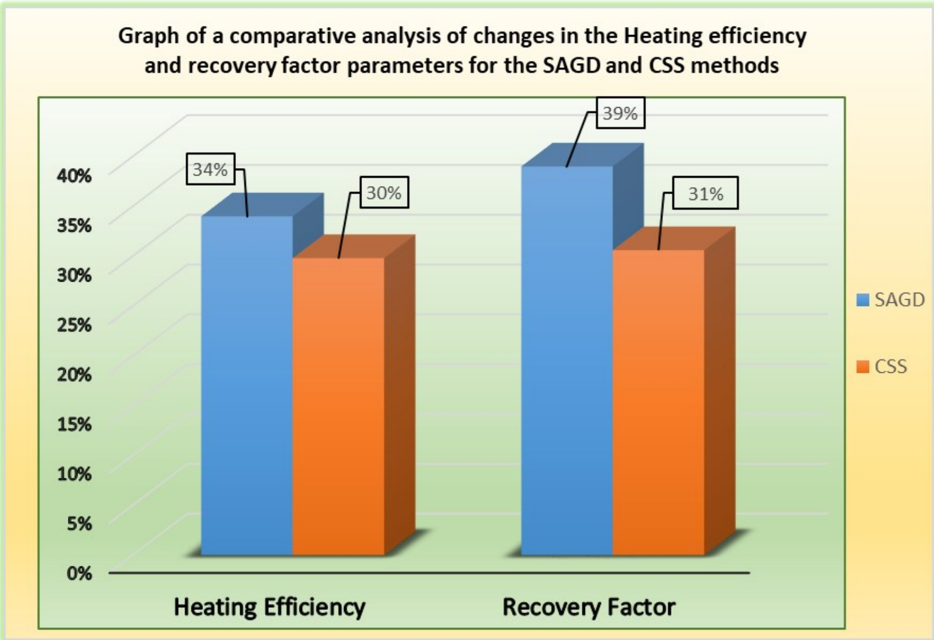

Fig. 2 The Graph of a Comparative Analysis of Changes in the Heating Efficiency and Recovery Factor Parameters for the SAGD and CSS Methods.

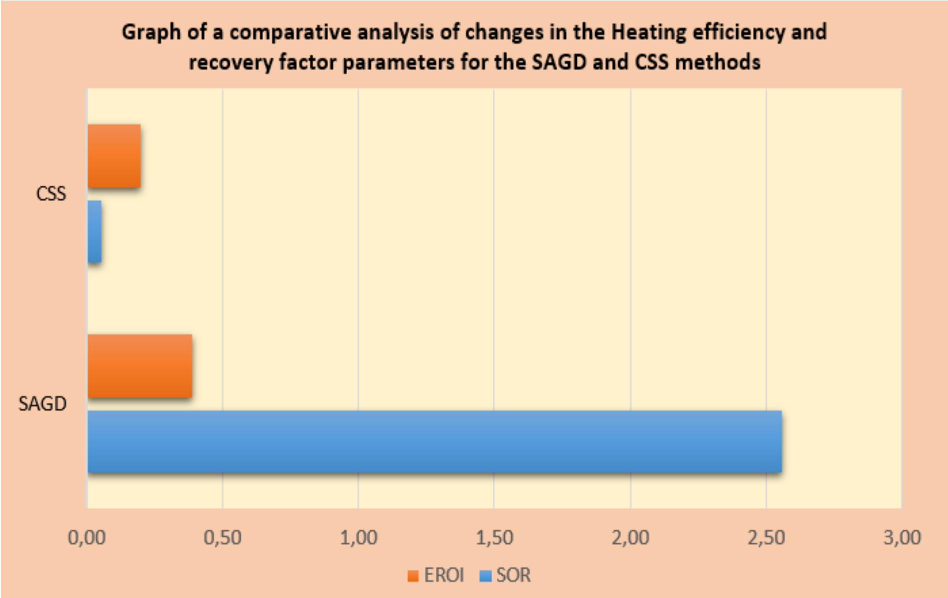

Fig. 3 The Graph of a Comparative Analysis of Changes in the EROI and SOR for the SAGD and CSS Methods.

12.CONCLUSION

Based on calculations of the five parameters (heating efficiency, recovery factor, production rate, SOR, and EROI), SAGD is more efficient than CSS. The heating efficiency of SAGD is higher than that of CSS, indicating that less energy is lost during heating. Additionally, SAGD has a higher recovery factor, meaning more oil can be produced from the same number of resources. SAGD has a higher recovery factor (approximately 39%) than CSS (approximately 30%). This means that more oil can be recovered from the reservoir using SAGD. Moreover, SAGD has a higher daily production rate than CSS, resulting in greater per-day oil production. With respect to steam efficiency, a lower steam–oil ratio means less steam is required per unit of oil. Our model yields SOR_SAGD ≈ 2.56 and SOR_CSS ≈ 5.40; therefore, SAGD is less steam-intensive than CSS under the studied conditions. A steam-oil ratio (SOR) is a measure of the efficiency of thermal recovery methods. A lower SOR indicates that less steam is required to produce a barrel of oil. The SOR for SAGD is 2.56, while for CSS it is 0.054. This means that SAGD is less steam-intensive and more efficient. Finally, the EROI for SAGD is higher than that for CSS, indicating that it requires less energy input to produce the same amount of energy output. The EROI for SAGD is 0.39, while for CSS it is 0.199. Although the difference is not significant, SAGD still has a slightly higher EROI, suggesting it is more energy-efficient. The well spacing for SAGD is 20 meters, while for CSS it is 100 meters. SAGD commonly employs closer injector–producer spacing (here, 20 m vs. 100 m in CSS), which increases healthy health density but improves reservoir contact; the net surface footprint and economics depend on pad design and are beyond the scope of this study. Therefore, based on these calculations, SAGD is a more efficient method for producing heavy oil from oil sands. In summary, SAGD is the more effective method for developing heavy oil reservoirs, based on a higher recovery factor, higher production rate, lower SOR, slightly higher EROI, and lower well-spacing requirements. This screening-level analysis assumes a homogeneous, isotropic reservoir, constant boundary pressure, fixed steam quality and temperature. It omits explicit wellbore and formation heat losses, geomechanical coupling, and a complete facility energy balance. Consequently, the reported EROI values are approximate, and project-specific infrastructure may affect the absolute numbers. These assumptions are standard for first-order comparative models and do not affect the qualitative ranking observed here.

REFERENCES

[1] Santos RG, Loh W, Bannwart AC, Trevisam OV. **An Overview of Heavy Oil Properties and Their Recovery and Transportation Methods.** *Brazilian Journal of Chemical Engineering* 2014; **31**(3): 571–590.

[2] Meyer RF, Attanasi ED. **Heavy Oil and Natural Bitumen: Strategic Petroleum Resources.** *United States Geological Survey USGS* 2003.

[3] Ali MA, Nofal WA. **Application of High-Performance Liquid Chromatography for Hydrocarbon Group Type Analysis of Crude Oils.** *Fuel Science and Technology International* 1994; **12**: 21–33.

[4] Lanier D. **Heavy Oil – A Significant Energy Source for the 21st Century.** *UNITAR Centre for Heavy Crude and Tar Sands* 1998; **1998**: 039.

[5] Butler RM. **A New Approach to the Modelling of Steam-Assisted Gravity Drainage.** *Journal of Canadian Petroleum Technology* 1985; **24**(3): 42–51.

[6] Butler RM. **Steam-Assisted Gravity Drainage: Concept, Development, Performance and Future.** *Journal of Canadian Petroleum Technology* 1994; **33**(2): 44–50.

[7] Donaldson EC, Chilingarian EV, Yen TF. **Enhanced Oil Recovery I – Fundamentals and Analyses.** *Elsevier Science Publishing*, Amsterdam; 1985.

[8] Filina OA, Konyukhov VY, Makarov AA. **Improvement of Operational Reliability of Units and Elements of Dump Trucks Taking into Account the Least Reliable Elements of the System.** *World Electric Vehicle Journal* 2024; **15**: 365.

[9] Green DW, Willhite GP. **Enhanced Oil Recovery.** *SPE Textbook Series, Society of Petroleum Engineers*, Houston, USA; 1998.

[10] Alvarado V, Manrique E. **Enhanced Oil Recovery: An Updated Review.** *Energies* 2010; **3**: 1529–1575.

[11] Butler RM. **Thermal Recovery of Oil and Bitumen.** *Prentice Hall*, New Jersey, USA; 1991.

[12] Van Poolen HK. **Fundamentals of Enhanced Oil Recovery.** *Pennwell Publishers*, Tulsa, USA; 1981.

[13] Pogrebnoy AV, Efremenkov EA, Valuev DV, Boltrushevich AE. **Improving the Reliability of Current Collectors in Electric Vehicles.** *Mathematics* 2025; **13**: 2022.

[14] Scott GR. **Comparison of CSS and SAGD Performance in the Clearwater Formation at Cold Lake.** *SPE/Petroleum Society of CIM/CHOA Thermal Operation and Heavy Oil Symposium* 2002.

[15] Bybee K. **Comparison of Cyclic Steam Stimulation and Steam-Assisted Gravity Drainage.** *Journal of Petroleum Technology* 2015; **55**(6): 68–69.

[16] Tattimbek G, Sherov KT, Absadykov BN, Sikhimbayev MR. **Study the Method of Thermal Frictional Treatment of Tooth Gap for Large-Modular Cylindrical Gears.** *Sustainable Development of Mountain Territories* 2025; **17**(1): 350–361.

[17] Klyuev RV, Yegorova EV, Bosikov II, Tsidaev BS. **Evaluation of the Use of Effective Technologies for Increasing the Sustainable Development of the Natural and Technical Systems of the Oil and Gas Complex.** *Sustainable Development of Mountain Territories* 2018; **10**(3): 392–403.

[18] Batuhtina IY, Batuhtin AG, Baranovskaja MG. **Mathematical Modelling of Mass Transfer of Dust-Air Mixture to Increase the Solid Fuel Combustion Efficiency.** *Sustainable Development of Mountain Territories* 2024; **16**(4): 1438–1449.

[19] Shayganpour F. **Comparison of CSS and SAGD in Cold Lake.** *Department of Chemical Petroleum Engineering, University of Calgary*, Calgary, Alberta; 2015.

[20] Malozyomov BV, Martyushev NV, Babyr NV, Pogrebnoy AV, Efremenkov EA, Valuev DV, Boltrushevich AE. **Modelling of Reliability Indicators of a Mining Plant.** *Mathematics* 2024; **12**: 2842.

[21] Irani M, Ghannadi S. **Understanding the Heat-Transfer Mechanism in the Steam-Assisted Gravity-Drainage (SAGD) Process and Comparing the Conduction and Convection Flux in Bitumen Reservoirs.** *SPE Journal* 2013; **18**(1): 134–145.

[22] Irani M, Gates I. **Understanding the Convection Heat-Transfer Mechanism in the Steam-Assisted Gravity-Drainage (SAGD) Process.** *SPE Journal* 2013; **18**(6): 1202–1215.

[23] Mijura K, Wang J. **An Analytical Model to Predict Cumulative Steam/Oil Ratio (CSOR) in Thermal-Recovery SAGD Process.** *Journal of Canadian Petroleum Technology* 2010; **51**(4): 268–275.

[24] Ghanabari E, Mighani S, Shaabani E, Alipour R. **Improving SAGD Performance by Combining with CSS.** *Amirkabir University of Technology* 2011.