Supercritical CO2: The Solution to Sustainable Oil Sand Extraction

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Abstract

Fossil fuels account for 81%[1] of energy generation globally and have prevailed as the dominant source of energy despite their environmental repercussions. Bitumen, a source of oil encapsulated in tar sand, has become particularly prevalent as conventional oil sources dwindle. Traditional oil extraction methods are impractical for this viscous substance; thus, rapidly-evolving innovations were devised to accommodate its drainage. While current technologies are economically prosperous and eco-satisfactory for bitumen, they can bear severe environmental consequences and limitations, be energy-exhaustive, and release harmful byproducts with the recovery of oil. The use of supercritical CO_2 to extract bitumen is capable of greater yields and better sustainability than its counterparts. Moreover, it addresses the issue of the dangerously abundant anthropogenic gases accumulated from the past decade. At an oil recovery efficiency of 29.6%,[2] SC-CO_2 significantly outperforms methods such as water flooding (2-20% efficiency),[3] with mitigated environmental damage. Moreover, this method is predominantly dependent on carbon dioxide, a renewable resource, which can remedy the ever-increasing greenhouse gas emissions produced by industries. With its environmental and economic feasibility, future projections for the industrial application of SC-CO_2 oil extraction are promising.

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1. Introduction

Over the decades, Canada's oil industry gradually rose to prominence in the global market as advanced technologies and extraction methods were implemented, eventually becoming the fourth leading oil producer in the world as of 2019.[4] The country is projected to double its oil production by 2050, primarily due to the rise in crude oil production from Canada's tar sands. One of Canada's leading sources of crude oil is from its oil sands in Alberta. Since the early 20th century, scientists have begun developing bitumen extraction methods for Alberta's tar sands in Athabasca.[5]

The age of oil continues to face a recession in sustainability as conventional oil reserves are depleted and oil prices dramatically rise, driving the industry to turn to nonconventional sources such as tar sands.[6] As such, the increasing profit prospects of tar sand reserves have urged the industry to shift its focus to reservoirs like the Athabasca tar sands. However, in recent years, issues regarding tar sand oil extraction's negative environmental impacts have been an ongoing matter of discussion. The concerns mainly refer to the conservation of drinking water sources and the steep carbon dioxide (CO_2) emissions.

Beginning in 1951 with the Hot Water Separation Process developed by scientist Karl Clark, the use of water in oil production in the sands has been essential.[7] As a result, water pollution has become a significant concern regarding the continuation of oil extraction from the Athabasca sands. The EU once planned to label tar sand oil as highly polluting due to the excessive use of water and production of greenhouse gas emissions.[8] Despite pulling back from this plan, the sentiment remains that tar sand oil extraction is a costly and environmentally hazardous method of oil production compared to conventional oil production methods. The revised EU plan maintained the intention to assess and monitor pollution levels from the sands to take action when necessary to keep it from causing excessive environmental harm. That is to say that although tar sand oil has not been barred from its global economic value, there remain concerns about environmental sustainability.

Current tar sand oil production methods heavily rely on water usage, both in its liquid and gaseous form as steam. In the Athabasca sands, potable water's mass consumption greatly impacts the environment, as every barrel of oil extracted from the sands requires 2-5 barrels of water to produce.[9] Not only that, but the use of water creates toxic tailings that are stored in specific ponds to avoid contaminating the environment around it. Moreover, as access to drinking water continues to decline, some sources predict that the world may run out of accessible drinking water by 2050.[10] Thus, the development and implementation of a bitumen extraction method with minimal water usage would be greatly advantageous in the long run.

The prevailing methods of bitumen extraction from tar sands emit 14% more greenhouse gases than conventional oil extraction methods.[11] According to IHS Cambridge Energy Research Associates, 79 kg of greenhouse gases are emitted per barrel of bitumen from mining and upgrading tar sands. In comparison, 116 kg are emitted per barrel using the melting method, burning natural gas. As climate change becomes progressively alarming, the addition of excessive carbon dioxide emissions due to the impending expansion of the tar sand industry only worsens the planet's health. From an environmental standpoint, bitumen extraction from tar sands cannot continue as it is now, lest the problem festers into something humans can no longer control.

1.1. Proposed Green Tar Sand Oil Production Method using Supercritical CO_2

In light of the evident environmental drawbacks of tar sands, the current bitumen production methods are not sustainable. However, Canada's economy has massively relied on the sands as it supports hundreds of thousands of jobs and the financial stability of Canadian governments.[12] To allow the industry to continue its operations and prosper, establishing and implementing an environmentally friendly alternative extraction method is the focus of this literature review.

Studies and experiments within the past ten years have been conducted to test the primary effect of using supercritical CO_2 (SC-CO_2) in oil extraction, including bitumen extraction from tar sands. However, the feasibility and societal implementation facets have yet to be considered. Substantial adjustments may be required for its real-world application, but research shows that the use of SC-CO_2 is viable. Not only would it make use of existing carbon dioxide emissions, but it could also require less energy to extract the bitumen and much less water compared to ongoing methods.

2. Oil Sands Extraction Methods

Many technologies, machinery and operations exist for the extraction of bitumen: surface mining, cold heavy-oil production with sand (CHOPS) and steam-assisted gravity drainage (SAGD) are the most notable methods of oil recovery, while supercritical CO_2 is a relatively novel approach. This section aims to evaluate the benefits and disadvantages each process offers.

2.1. Surface Mining

The most common method of extracting bitumen from the Athabasca sands is through surface mining.[13] Bitumen-rich sand is gathered in a process called "extraction", where trucks scoop up and collect the surface sands. In "conditioning", the oil sand is broken up into large chunks and mixed with water to break the bonds holding the bitumen and sand together in order to prepare them for upgrading. Next, hot water is added to the mixture and three distinct layers can be observed in the stage called “separation”. At the bottom of the mixture is the sand, while bitumen froth rises to the top. The layer in between is a mechanical mixture of sand, water, fine clays, and minerals, known as tailings. In the final stage called “froth treatment”, the froth is diluted and the water and solid particles are removed. The leftover water and particle mixture are discharged in tailings ponds.

Surface mining uses excessive amounts of fresh water, and there are concerns regarding land usage. It requires the clearing of forests, vegetation, and topsoil, resulting in habitat loss and damaging the region’s agricultural prospects.[14] Moreover, mining releases toxic chemicals such as sulphur oxides, nitrogen oxides, hydrocarbons, and fine particulate matter.[15] Currently, however, the extraction stage cannot be eliminated as there are few other properly tested methods of bitumen extraction from shallow deposits. The upgrading stages can be altered to prevent further surplus energy and water consumption, as well as tailings.

2.1.1. Tailings Ponds

Tailings produced in the separation and froth treatment stages are discharged into tailings ponds near the mining sites. These ponds are one of surface mining’s major concerns, as the residual chemicals, minerals, and metals from the bitumen separation are left suspended in the ponds, making them toxic and environmentally hazardous.[9] If pond water seeps into nearby water sources, it would be a major contaminant and endanger the aquatic species and ecosystems. The water disposed of in tailings ponds takes many years to reclaim because the residue requires a long time to settle, making the ponds a substantial environmental threat.

2.2. Cold Heavy Oil Production with Sand (CHOPS)

Cold Heavy Oil Production with Sand (CHOPS) is a rapidly developing technology becoming increasingly widespread in the heavy oil industry. Characterized by its exclusive use in the Canadian heavy-oil belt and shallow wells, CHOPS has proven to be highly economical and beneficial for thin reservoirs.[16] The extraction process involves the deliberate initiation of sand influx into perforated oil wells, maintenance of sand influx during the well's productive life, and implementation of methods to separate the sand from the oil for disposal.

The success of CHOPS is undeniable, but several unique operational and environmental limitations have emerged in its application. CHOPS requires the management of unfiltered sand in large quantities in all production phases, making the procedure highly energy-intensive. CHOPS also produces sand aggressively as a byproduct, which can change the reservoir's physical and geomechanical properties, forming open channels known as wormholes[16]. Given that CHOPS’s ultimate recovery is between 5% to 15%,[17] a generous amount of oil remains in the reservoir which necessitates secondary enhanced extraction processes. However, the wormholes generated in CHOPS present a problem for follow-up exploitation methods that rely on the oil's displacement, as the holes act as a conduit for the displaced fluid to bypass the reservoir.

Additionally, due to the high solids content, CHOPS’s oil is not “pipeline” quality.[17] Consequently, the oil must be transported mechanically. The sites are visited systematically by tanker trucks to empty production takes. As a road must be present for the trucks to roam, seasonal weather conditions may pose as a hindrance to the transportation of these oils.

2.3. Steam-Assisted Gravity Drainage (SAGD)

Another prominent method of oil sand extraction is Steam-Assisted Gravity Drainage (SAGD), typically oriented for extraction in deeper reservoirs. SAGD posed a solution for the inability of conventional in situ methods to recover immobile and viscous bitumen[18]. The process involves drilling two parallel horizontal wells into an oil reservoir (see fig. 1). By injecting high-temperature steam into the upper bore, the oil would reduce its viscosity and drain into the lower chamber for pumping.[19] With the primary byproduct being steam, SAGD is environmentally adequate.

Although SAGD has extensive applications, there are a myriad of concerns associated with it. One of the foremost issues encountered is the inefficiency of steaming: heated bitumen will regain its viscosity as it is moving along a cold reservoir which prevents adequate flow.[19] Continual steam stimulation is necessary to achieve a consistent temperature; however, the overwhelming amount of heat and water required for SAGD makes it exhaustive and uneconomical in complex reservoirs with low-porosity. Moreover, the maximum oil recovery rarely exceeds 20% due to the tendency for steam to bypass.[20] Secondary combustion fronts present another problem. These disturbances occur near injection sites and can damage equipment and render the entire process a failure. Situations like these are exceedingly difficult to prevent as well, given that the operation is facilitated at dangerously high temperatures; if an emergency were to occur, SAGD cannot be halted. Thus, Steam-Assisted Gravitational Drainage is a considerably risky and inefficient form of oil extraction.

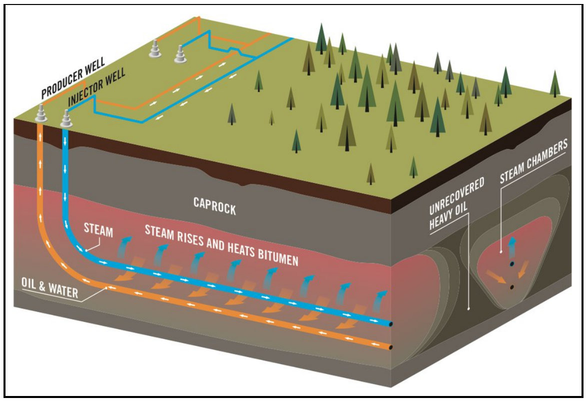

Figure 1: Steam-Assisted Gravity drainage (Source: JWN, 2016[21])

2.4. Supercritical CO, Oil Extraction

Studies within the past decade have shown promising results for the use of SC-CO_2 in bitumen extraction from tar sand. SC-CO_2 provides many advantages due to its composition. The supercritical state of substances has both qualities of a liquid and a gas. For SC-CO_2, its gaseous properties allow for efficient mass-transfer, while its liquid properties help it act as an effective solvent.[22] Both of these properties are favourable for bitumen extraction. Acting as a gas, the SC-CO_2 can permeate solid tar sand to extract the bitumen, and the bitumen solute can dissolve in the SC-CO_2 as a solvent to separate itself from the tar sand's solid matrix.

Furthermore, supercritical fluids have little to no surface tension, allowing them to penetrate low-porosity materials easily. This does not prove to be a major advantage, as tar sands typically are quite high in porosity,[23] although this property simply gives more reason as to the benefits of SC-CO_2. SC-CO_2 is also low in viscosity, allowing it to flow swiftly which increases extraction efficiency in saving time.[24]

Extraction can be even more efficient when SC-CO_2 is used in tandem with a co-solvent.[25] The purpose of a co-solvent is either to dilute the solute—bitumen—to decrease its viscosity or to increase the density of the SC-CO_2.[24] It has been found that the solubility of

SC-CO_2 generally increases as the density increases, so the addition of a co-solvent with a higher molecular weight than that of SC-CO_2 and increasing the overall density of the solvent would prove to be beneficial.[26]

Using SC-CO_2 in bitumen extraction reduces sand preparation time since extraction can be performed using solid or semi-solid tar sand,[27] making it efficient in comparison to other bitumen upgrading methods.

2.4.1. Bitumen Extraction Trials

In this study, the two major works cited that centred on bitumen extraction from tar sand were Rudyk and Spirov's "Upgrading and Extraction of Bitumen from Nigerian Tar Sand by Supercritical Carbon Dioxide"[2] and Rudyk's "The Bitumen Upgrading of Nigerian Oil Sand by Supercritical Carbon Dioxide Modified with Alcohols".[24] General processes were derived from Rudyk and Spirov's "Effect of RegenOx Oxidant As a Modifier on Crude Oil Extraction by Supercritical Carbon Dioxide".[28]

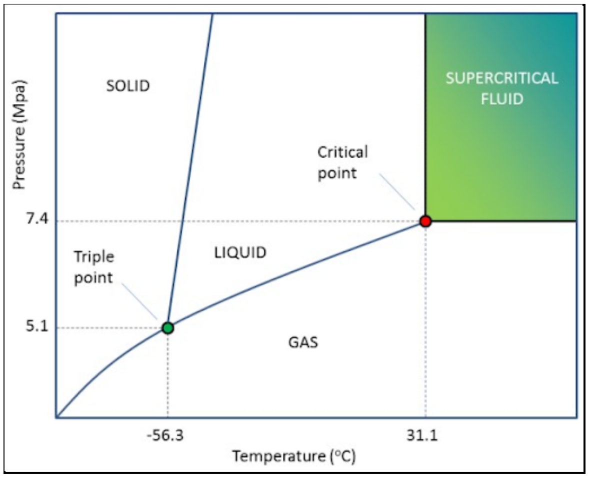

Figure 2: States of CO_2 depending on temperature (K) and pressure (bar) (Source: Supercritical CO_2, 2010[29])

Fig. 2 shows that CO_2 becomes a supercritical fluid around 32.1℃ and 7.38 MPa.[30] Since higher pressure results in higher solubility and higher temperature permits more efficient melting of bitumen, extraction has always been conducted at around 110℃[28] and between 50-65 MPa,[2] so as to keep the experiments safe yet efficient. Although solubility typically increases with density in supercritical fluids, Rudyk and Spirov found that the extraction rates of SC-CO_2 dropped steeply after the pressure surpassed 60 MPa at 65 MPa.[2] The best pressures for extraction were 50 and 60 MPa.

In the experiments, CO_2 was pumped into an extraction cell sitting within an oven set at 110℃. The tar sand sample and the SC-CO_2 interacted for 30 minutes in static mode in the extraction cell before entering dynamic mode, in which open and exit valves from the cell were opened to pump out the extracted bitumen and vent out the gas. Each sample underwent three runs of extraction before being taken out to maximize oil extraction from the samples.

The use of co-solvents was present in these trials, using distilled water, salt water, and ethanol. Bitumen yield varied depending on the co-solvents used. In Rudyk and Spirov's experiments, it was concluded that the extraction using SC-CO_2 had a yield similar to water flooding oil reservoirs. Waterflooding's oil recovery yield is around 2-20% of oil present in tar sand[3], while the usage of water and saltwater as co-solvents yielded 23.6% and 29.6% respectively at 50 MPa.[2] As for ethanol, the yield averaged at 21%.[24]

The extracted bitumen with ethanol or salty water as co-solvents was a yellow-orange hue due to the lack of petcoke present,[2] a byproduct typically present in extracted bitumen that would need to be removed in the bitumen upgrading stage. As the bitumen proved to be purer than that from other extraction methods, the energy required for bitumen upgrading would be greatly decreased.

3. Supercritical CO_2 Oil Extraction System Implementation

3.1. Supercritical CO_2 Oil Extraction System

3.1.1. System Apparatus

To implement the SC-CO_2 oil extraction system into real-world conditions, modifications to the small-scale experimental system setups are necessary. Fig. 3 lays out the industrial system, wherein necessary changes have been implemented.

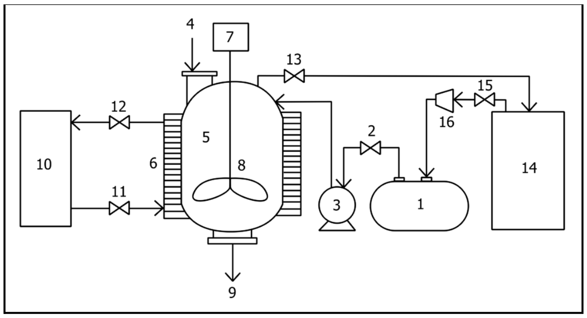

Figure 3: Flowsheet diagram for industrial bitumen extraction using supercritical CO_2: (1) CO_2 storage tank, (2) CO_2 inlet valve, (3) pump, (4) prepared melted tar sand opening, (5) extraction tank, (6) jacketed heater, (7) motor, (8) tank mixer, (9) sand discharge exit, (10) water heater, (11) hot water inlet valve, (12) cool water outlet valve, (13) extract outlet valve, (14) product receiving tank, (15) CO_2 outlet valve, (16) CO_2 compressor. Modified from Rudyk and Spirov.[28]

In laboratory-scale experiments set up for testing the effectiveness of SC-CO_2 as a solvent for bitumen, the apparatus includes a CO_2 storage tank, a cooler, an oven, and the exit pipe. Within the oven contains a pump, a preheat coil, the extraction cell holding the tar sand sample, and a vent.

The usage of ovens to contain the extraction cell would be impractical in large-scale extraction facilities, and as such, would be replaced by the usage of a jacketed heater on the outside of the extraction tanks. The chosen jacketed heater type is the half-pipe coil jacket.[31] In comparison to other jacketed vessels such as conventional jackets, it saves energy and increases heating efficiency. The jacket must be situated on the outside in lieu of an internal coil to avoid cleaning complications. The jacketed heater would use hot water instead of steam, as CO_2 reaches a supercritical state at around 32.1℃ and 7.38 MPa.[30] The temperature of steam would be too high to ensure the safety of the system during operation in case equipment were to malfunction.

3.1.2. System Process

The process begins with extraction, the same as in surface mining, wherein trucks excavate and collect the bitumen-rich sand. This stage cannot be avoided for sand near the surface, as environmentally hazardous as it is. The collected sand is then transported to the extraction facilities. Mined areas should be replanted and taken care of once cleared of oil-abundant sand to ensure as little habitat loss and soil fertility disruption as possible.

Once in the extraction facility, the tar sand is crushed and melted in a tank at 120℃ for a duration of 2 hours[28] to decrease the viscosity of the bitumen and loosen its bonds with the sand. During this stage, a saltwater co-solvent is added and mixed in with the crushed sand. The co-solvent is prepared by adding 25g of NaCl to every litre of distilled water.[2] The ratio of the water to sand weight would be 1:5, as used in Rudyk and Spirov's experiments.[2] The tar sand is then transferred to the extraction tank through (4) the tank's top opening, as seen in fig. 3. Hot water from the (10) water heater is pumped into (6) the jacketed heater to maintain a temperature of 110℃[28] to increase extraction efficiency while keeping the energy usage to a minimum. (11) The water inlet and (12) outlet valves are opened to control the temperature and reheat any cooled water continuously to avoid temperature inconsistencies during the extraction process.

(2) The CO_2 inlet valve is then opened, and CO_2 is injected into (5) the extraction tank

via pipes by (3) the pump until the tank reaches the desired pressure of 50 MPa[2] for the CO_2 to reach a supercritical state. CO_2 flow into the tank is then stopped by closing the valve. (7) The motor for the (8) tank mixer is turned on, and the extraction tank is left for 30 minutes for the SC-CO_2 and the tar sand to interact in static mode.[28] The process then enters dynamic mode, and (13) the extract outlet valve and the (2) CO_2 inlet valve are opened to release the SC-CO_2, saltwater vapour, and bitumen mixture into (14) the product receiving tank. Once received, both valves are closed. As the SC-CO_2 and saltwater vapour depressurizes and cools, the remaining water and bitumen are separated from the SC-CO_2 and remain at the bottom of the tank. (15) The CO_2 outlet valve is then opened, allowing the gas to be transported back to the CO_2 storage tank. On the way, it passes through (16) the compressor in order to enter the pressurized storage tank. This way, CO_2 is reused as much as possible and the resupplying of it is kept at a minimum for better economics.

The process of pressurizing CO_2, having it interact with the tar sand, then collecting the extract is repeated twice more after the initial extraction to ensure that as much bitumen is produced from the sand as possible. Following the third run, (7) the motor for the mixer is turned off and (9) the sand discharge exit is opened and the leftover material—a mix of sand and minerals—is cleared from the tank to prepare for the next batch. Once the product receiving tank is at capacity since the water and bitumen are immiscible, they are then separated and the bitumen is collected. The water can be reused as much as possible as salt is added to it to create the co-solvent.

CO_2 loss from opening the extraction tank is to be expected, and therefore the CO_2 storage tank must be resupplied when there is a deficiency of it.

3.2. CO_2 Capture

The consequences of climate change have necessitated post-combustion capture of CO2, particularly in flue gas and power plant emissions, to reduce anthropogenic pollution.[32] CO_2 capture not only mitigates global warming but also acquires the fuel that enables the proposed SC-CO_2 oil extraction system to function. Methods such as Direct Air Capture (DAC) and Pressure Swing Adsorption (PSA) are increasingly adopted in industries to manage carbon footprint in light of the carbon crisis. These technologies employ familiar mechanisms such as membrane separation and adsorption, thereby producing sizable and predictable success in their performance; however, most are expensive, inefficient and inapplicable to existing power plants.[32] A relatively recent innovation utilizes electrochemical cells in a battery-like structure for CO_2 capture. Unlike its counterparts, the Electro-swing Reactive Adsorption (ERA) acts directly upon targeted molecules (instead of the mediums) through electrochemistry, which substantially boosts efficiency[32]. With the extraction system addressed hitherto, the focus will shift to evaluating and analyzing ERA as a CO2 capturing method to implement the oil extraction system potentially.

Electro-swing Reactive Adsorption is a novel technology for CO2 capture that is easily implementable without compromising the outlet stream's purity.[32] The high desorption offered by this system could halve the compression costs required for geological sequestration and minimal use of water and heat could eliminate costs associated with steam generation.[32] The system engineered by MIT is essentially a specialized battery alternating between a state of charging, during which the feed gas is blown through the system, and discharging when the concentrated CO2 is flushed out for liquidation and transport. The electrochemical reaction occurs at the electrodes' surface, coated with a compound called poly-anthraquinone composited with carbon nanotubes.[33] The electrode has natural incivility toward the CO2, attracting its molecule in the feed gas even at low concentration. Upon discharge of the battery, the reverse action ensues where the pure stream of CO2 is collected. Given that the ERA system operates at room temperature and normal air pressure, it is a very energy-efficient alternative.

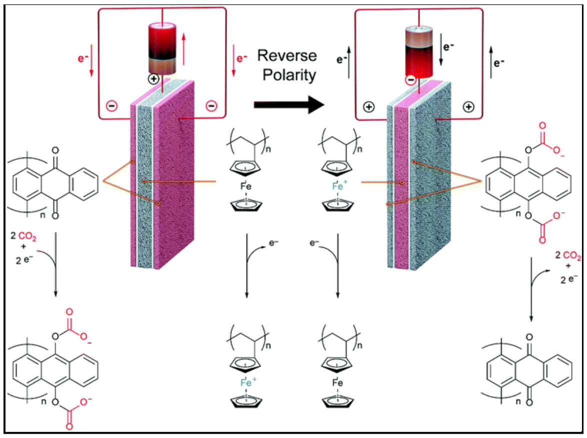

Figure 4: Diagram of a single electro-swing adsorption electrochemical cell with porous electrodes. The outer electrodes can capture CO2 and release the CO_2 on reversal of the polarity. The inner elector serves as an electron source and a sink for quinone reduction and oxidation. (Source: Voskian & Hatton, 2019[33])

The advantages posed by ERA are both evident in its design and data. The study conducted by Voskian & Hatton indicates an efficiency of approximately 86 kJ per mole of CO2 captured, with an estimated 90% CO_2 released.[33] On an extensive and potentially industrial scale, the electrochemical cells can operate in parallel, with flue gas alternating throughout each pair to provide a consistent stream of CO2. The 2019 study proved the ERA system could withstand at least 7,000 cycles, with estimates that improvements can see upwards of 20,000 to 50,000 cycles.[33] Furthermore, mass production is not unlikely because standard chemical processing methods are sufficient for manufacturing the electrodes at reasonable prices of tens of dollars per square meter.[33] Hence, the proposed SC-CO2 oil extraction system favours the efficient, economically feasible and capitally effective Electro-swing Reactive Adsorption.

4. Environmental and Economic Sustainability of Supercritical CO2 Oil Extraction

4.1. Environmental Sustainability

The SC-CO_2 oil extraction system, from beginning to end, is a more environmentally friendly extraction method than many of its alternatives currently being used in the industry. The system reuses CO_2 waste—a renewable greenhouse gas—from power plants and within the bitumen extraction system itself. This alone is an environmentally sustainable feature of the system. Freezing the CO_2 into a liquid form also saves space in transportation, reducing the number of trips necessary to deliver the substance to the extraction facilities.

Furthermore, the consumption of energy is similar to or lower than that of other extraction methods, as energy is mainly needed to operate the equipment during the extraction and upgrading processes as noted in section 3.1.2.. The usage of water is also significantly reduced. For instance, surface mining requires 3-4 barrels of water in order to produce one barrel of bitumen.[34] Meanwhile, in the SC-CO_2 system where it is used only as a solvent, it uses 1 part saltwater for 5 parts tar sand. If the bitumen yield is 29.6%, it would only require around 0.68 barrels of water per barrel of bitumen. Moreover, the saltwater co-solvent can be recollected and reused as much as possible, although gradual losses are to be expected.

Finally, tailings would not be produced, as the petcoke and other minerals from the sands are immediately separated from the bitumen already. Tailings ponds would not be an issue as a result of this.

4.2. Economic Advantages

With environmental sustainability comes long-term economic prosperity, as bitumen is an abundant source of fossil fuels while conventional sources peter out. Additionally, implementing this system would radically reduce long-term costs associated with pollution, environmental policies, and energy. Power plant operation companies may be open to monetary compensation for collecting CO_2 from their plants since otherwise, they would have to pay carbon taxes to the government. Furthermore, since many components of the system can be reused, such as the water and CO_2 solvents, resupplying them would require fewer expenses in both purchase and transportation. The advantageous efficiency of the extraction system owing to the physical properties of SC-CO_2—low viscosity, easy penetration of solid/semi-solid substances, solubility, and smooth flow—save time and energy during the extraction process.

5. Conclusions and Future Perspectives

The supercritical CO_2 oil extraction system has been proposed and presented as a sustainable alternative to conventional drainage methods. With each component selected mindfully, the extraction system offers tangible benefits toward the energy sector's overall success. Environmentally viable and amply economical, SC-CO_2 proves to be a revolutionary bitumen oil extraction tool that removes the necessity of enhanced follow-up procedures while causing minimal geomechanical irritation.

As bitumen becomes increasingly desirable, SC-CO_2 could greatly increase economic profit from its exploitation as a fossil fuel. With Alberta becoming a hub for this resource, future industrial implementation of this system could further propel Canada's standing in the global oil market. Additional research and investment would also benefit the system by decreasing its dependency on surface mining and formulating a greener alternative physical tar sand collection. Moreover, if engineers advance the SC-CO_2 design for better portability, its functionality *on* the site would unleash immeasurable potential as the convenience, efficiency and speed of oil-extraction would sky-rocket in an unprecedented way. Actualizing the system to produce on-site would also allow access to deeper bitumen reservoirs, further expanding this technology's application and versatility. Given that SC-CO_2 primarily sources post-combustion CO_2, supply will likely derive from existing industry emissions. In this case, both parties—SC-CO_2 and the enterprise in question—will mutually gain from an exchange and even long-term agreement; SC-CO_2 capitalizes on the anthropogenic flue gas while the business abides by environmental policies without facing fines. From reducing sand preparation time to significantly improving efficiency, SC-CO_2 is undoubtedly a tool that could transform the future of bitumen oil recovery.

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