J. Ind. Geophys. Union (January 2016)
Special Volume-1/ 2016 pp: 5-12

Carbon Dioxide Sequestration During Enhanced Oil Recovery: Operational and Economical Aspects

G.P. Karmakar

Department of Mining Engineering, Indian Institute of Technology, Kharagpur – 721302, INDIA.
E-mail: gpkarmakar@gmail.com

ABSTRACT

Rising oil prices coupled with continuously declining conventional oil production has led to significant use of Enhanced Oil Recovery (EOR) methods. Extensive laboratory studies, pilot projects and real field evaluations of the potential EOR methods have proved that the upcoming carbon dioxide flooding is one of the most promising recovery methods, which is being used on a large scale in many countries including the U.S., Canada and U.A.E. Carbon dioxide injection is being done in different modes: in miscible, near miscible or immiscible forms after water flooding as an EOR method, as a secondary displacement method, for producing well stimulation and for carbonated water flooding. During the CO_2 sequestration, CO_2 is retained in the reservoir by increasing its physical trapping or solubility in reservoir fluids, whereas during CO_2 - EOR process, oil recovery is maximized with a minimum amount of retention of CO_2 in the reservoir.

This paper presents a comprehensive review on the current status of CO_2 flooding processes with a critical analysis of latest CO_2 flooding projects featuring recent developments and operational problems and their solutions associated with those processes.

INTRODUCTION

The use of carbon dioxide as an oil-displacing agent has been investigated for many years and used for recovering oil from hydrocarbon reservoirs during 1920-1930 (Mangalsingh and Jagai, 1996). Extensive laboratory studies, pilot projects and field studies have further confirmed the efficacy of the technique in enhanced recovery of oil (Holm and Josendal, 1974). In 1945, Poettmann and Katz discussed the phase behavior of CO_2 and paraffin systems. Their studies indicated that for heavier crude, the increase in oil volume is normally between 10-22% and the viscosity reduction is up to less than 0.1 of the original value. The high solubility of CO_2 in oil and resultant reduction in viscosity attracted the investigators to study this process in laboratory. The investigations included fluid injection processes using continuous CO_2 or a single slug of CO_2 followed by water or carbonated water (Holm, 1987). The first successful process was carried out in 1958 at Oklahama (Khatib et al., 1981). In the 1950's and 60's, the application of CO_2 was primarily as a miscible displacing fluid and certain limitations in the process were realized. These limitations led to concerted investigations on CO_2, for immiscible displacement . Field applications of immiscible CO_2 were carried out in the 1970s. Due to certain deficiencies in continuous CO_2 process, the water alternating gas (WAG) process was introduced in the 1980s. A comprehensive review of the immiscible process in heavy and light oil reservoirs was done by earlier researchers (Khatib et al., 1981). Recently, enhanced oil recovery using carbon dioxide has become one of the most popular investigations among the researchers and the oil producers.

MOST COMMON TYPES OF CO_2 FLOODING

Elaborated studies of phase behavior and CO_2 flood performance in laboratories and fields have brought into light certain mechanisms by which CO_2 displaces oil. These mechanisms in general are related to the phase behavior of CO_2-crude oil mixes.

These are: (1) immiscible CO_2 drive, (2) hydrocarbon-CO_2 miscible drive, (3) hydrocarbon vaporization, (4) direct miscible CO_2 drive and, (5) multiple contact dynamic miscible drive.

HOT CO_2 FLOODING

A new CO_2 - EOR technique "Hot CO_2 Flooding" is being worked out these days in Bati Raman heavy oil field in Turkey. This technique (Picha, 2007; Issever et al., 1993) is a combination of thermal and solvent techniques, wherein the hot CO_2 heats the reservoir and reduces oil viscosity. This enables partial miscibility with the oil, thus leading to improvement in oil mobility and recovery factor. The operating temperature of hot CO_2 is decided according to the reservoir temperature and oil property and is kept above the critical point in CO_2 phase diagram. Hot CO_2 can similarly be injected in different ways such as continuous injection, alternating with water injection or followed by steam injection. According to the theoretical calculations, the ultimate recovery increased from 10% in case of conventional CO_2 flooding to 13% in case of hot CO_2 flooding, due to marginal reduction in oil viscosity and increase in swelling factor.

WATER-ALTERNATING-GAS (WAG) PROCESS

Water-alternating-gas (WAG) process is a combination of two traditional techniques of improved hydrocarbon recovery: water flooding and gas injection, which can be defined as a short-cycle alteration of definite ratios of water and CO_2. The first field application of WAG is attributed to the North Pembina field in Alberta, Canada, by Mobil in 1957. Laboratory models (Rogers and Grigg, 2001) developed early in the history of flooding showed that simultaneous water/gas injection had sweep efficiency as high as 90% compared to 60% for gas alone. The displacement mechanism caused by the WAG process occurs in a three phase regime; the cyclic nature of the process creates a combination of imbibition and drainage (Christensen et al., 2001). Optimum conditions of oil displacement are achieved if the gas and water have equal velocity in the reservoir. Important technical factors affecting WAG performance that have been identified are heterogeneity, wettability, fluid properties, miscibility conditions, injection techniques, WAG parameters, physical dispersion, and flow geometry (Surguchev et al., 1992).

OTHER METHODS

Another method was introduced where mobility control could be achieved by adding one or more of certain surface active chemicals to carbon dioxide, which is either in a liquid or supercritical state, before it is injected into wells (Heller et al., 1983). The surface active chemicals have sufficient solubility in dense carbon dioxide to cause water that is already present in the oil reservoir to emulsify with the carbon dioxide. The emulsion decreases the mobility of the injected carbon dioxide. Upon continued injection of carbon dioxide, flow is diverted to other less permeable zones of the reservoir or away from the top of the reservoir thereby improving the vertical conformance of the carbon dioxide flood and substantially increasing the oil recovered by the flooding process. In some cases carbon dioxide flooding is carried out with a premixed transition zone of carbon dioxide and crude oil components. This method consists of injecting into the formation a premixed transition zone slug comprising carbon dioxide and said crude oil components at said critical concentrations, formation temperature and said selected pressure; and injecting a drive fluid into the formation after the premixed transition zone slug (Heller et al., 1982).

In order to identify a potential reservoir for CO_2 flooding, a screening criteria based on technical as well as economic factors may be helpful. The reservoirs are screened for economic feasibility according to capital costs, operation expenses, availability of CO_2 and then ranked based on the economics, namely ratio of derived revenue based on day to day international market rates and production costs. Prior to proceeding with the pilot production operations, appropriate coring, core analyses, and logging operations were carried out to evaluate certain parameters, which were compared with the performance of a pilot field test.

LATEST CO_2 FLOODING PROJECTS

It has been reported that the total number of CO_2 projects in operation so far has increased in the U. S. and worldwide (Moritis, 1996). Recently, the promising results of two gas injection pilot initiatives of a full field non-miscible gas injection schemes, implemented in a carbonate reservoir in Abu Dhabi, U. A. E., have been reported (Shedid et al., 2007). The study stressed the importance of a detailed reservoir characterization and maximum flexibility in the development design and close monitoring of the reservoir response. Of the four immiscible CO_2 pilot floods conducted in Trinidad from 1973 to 2003 (Mohammed-Singh and Singhal, 2004), one project with a large throughput of CO_2, indicates incremental oil recovery between 2-8% of the OOIP with predicted ultimate recoveries of 4-9% of the original-oil-in-place (OOIP). The projects were conducted in a gravity stable mode after primary, secondary and tertiary production (after natural gas and water injection). Cumulative CO_2 utilizations improved with efficient production practices and ranged from 3-11 MCF/bbl till 2003. In this field, oil recovery improved as more production wells were added downstream of the injection wells. In some of the projects, production increase was observed even after discontinuation of CO_2 injection (supply interruptions) aided by water influx and gravity stabilization. It was concluded that immiscible gas injection projects should be implemented with special attention to GOR control at the producers, and also the gas injection rates should be selected such that oil contributions from CO_2 injection as well as water influx are optimized. Evaluation of the application of CO_2 injection into a Norwegian oil reservoir showed that this application produced 63 % of initial-oil-in-place (IOIP) while water injection recovered 43 % IOIP (Lindeberg and Holt, 1994). The increment in oil recovery by miscible flooding was attributed to improvement in displacement efficiency and reduction in oil viscosity. A review of twenty-five CO_2 projects as a maturing EOR process indicated that the application of CO_2 floods provided good increments in oil recovery (Grigg and Schechter, 1997). The study presented some concerns about high mobility of CO_2 and its early breakthrough. The study also indicated that most of the newer floods and some older floods increased CO_2 slug size, injected CO_2 continuously till CO_2 breakthrough, and then converted to water-alternating-gas (WAG) process. It has been observed that miscible CO_2 flooding might recover up to 8 % to 16 % of the OOIP depending on the reservoir depth and other peculiarities of the reservoir and the crude oil characteristics. The study also indicated that maximum CO_2 flood recovery could be plus 10 % of OOIP after matured water flooding recovery (Jeschke et al., 2000). A case study of the Dulang field in Malaysia was carried out to evaluate the CO_2 injection. The study included phase behavior studies, vaporization test and core displacement tests. The results indicated that 15 % of the initial stock oil in place was produced using CO_2 flooding at the initial reservoir pressure of 1800 psig. The study also showed that the application was capable of extracting components heavier than heptanes (Zain et al., 2001). Using recombined fluid in a slim tube to determine the Minimum Miscibility Pressure (MMP) under different gas-oil ratio (GOR) and CO_2 concentrations proved that the main factors to enhance the oil recovery in CO_2 flooding were the oil swelling and the viscosity reduction (Yongmao et al., 2004). In the Neuquén Basin in west-central Argentina, with no prior CO_2 injection, viability and prospects of immiscible CO_2 flooding process in the Avile reservoir were found to be favorable with the results of core flood evaluation, compositional simulation and evaluation of facility requirements (Brush et al., 2000). This project was innovative in the sense that it assessed the feasibility of extracting previously vented CO_2 and injecting it again to recover additional oil and at the same time reduce green house gas emissions .The estimated increase in oil recovery was 4% of OOIP and the potential greenhouse gas emission reduction ranges from 185,000 to 714,000 carbon equivalent metric tons. Asghari et al., (2006) designed a model to predict the performance of CO_2 flooding in this field based on the data obtained from past water flooding performance and CO_2 rate injection by developing a correlation. It is estimated that implementation of CO_2 flood would extend the economical life of the field more than 25 years, with an incremental recovery prediction of 13% to 19%. The limitation in applying this correlation is that it can be applied only to existing CO_2 flood area, since the two correlations developed require some post-CO_2 flood data to develop constants. These correlations provide a very fast and practical method for determining the expansion area of an existing CO_2 flood operation. A recent example of the significance of this process can be seen in the Spraberry Trend area of West Texas (Montgomery et al., 2000), once known as the "largest uneconomical field in the world," which contains as much as 10 billion bbl of original oil in place. Despite five decades of production, including several large-scalewater flood projects, recovery from the Spraberry rarely exceeded 8-12%. A significant new effort has been launched to correct this situation and to evaluate the efficiency and economics of using CO_2 flooding to enhance recovery from Spraberry reservoirs. Laboratory study of CO_2 gravity drainage in Spraberry core suggests that significant additional oil can be recovered in this manner. Recently, a new approach (Liu et al., 2004) of studying the progress of carbon dioxide in reservoirs using ultrasound has been introduced. This may lead to unique monitoring the position of carbon dioxide, as well as visualizing the reality of the oil producing area. The problem of identifying the position and location of the immiscible or miscible layer is a critical issue in the method of carbon dioxide injection for oil producing bodies. Accurate knowledge of the position could lead to an ability to control the position of the carbon dioxide front affecting production, efficiency, economy, and in the end profitability. Some measures of digital signal processing are introduced to obtain position information of interfaces in porous medium and improve the resolution and accuracy of the location. Ultrasound has many advantages as a tool in underground probing, such as small size, low power consumption and safety.

CO_2 - EOR has been used by the oil and gas industry for over 40 years, but only recently has its potential as a carbon sequestration method been realized and investigated.

Currently, CO_2 - EOR comprises approximately more than 37 percent of all EOR being performed in the United States and it has been a leader in developing and using technologies for CO_2 - EOR by performing approximately 96 percent of worldwide CO_2 - EOR.

OPERATIONAL PROBLEMS IN THE FIELD

CORROSION

Carbon dioxide in the presence of water forms carbonic acid ,which produces corrosive environment. The corrosion can be minimized by having a separate injection facility for both these fluids, by using corrosion inhibitors and by using stainless steel wellheads and downhole equipments. The carbon dioxide should also be dehydrated at the source before it is compressed and transported (IPCC, 2005).

ASPHALTENE DEPOSITION IN CO_2 FLOODS

Asphaltenes are believed to exist as colloidal suspension in oil, stabilized by resins present and are in equilibrium with oil at reservoir condition. This equilibrium gets disturbed during production mainly due to pressure and temperature reductions and introduction of miscible gases and solvents, thus leading to loss in production and failures of Electrical Submersible Pumps (ESP), safety valves and other downhole equipment. In general, as more gas dissolves into the crude oil, the asphaltenes problem increases (Tin and Yen, 2000). In order to curb this problem several chemical inhibitors were introduced.

HANDLING OF THE PRODUCED CARBON DIOXIDE

The best solution to this is re-injection of CO_2 in the reservoirs to reduce the volume of CO_2 to be procured (Necmettin, 1991). It can be injected without processing or after separating it from associated gases. Finally all such proposals may be considered only after the economics of the processes are studied thoroughly.

SCIENCE AND ENGINEERING REQUIREMENTS FOR GEOLOGICAL CO_2 SEQUESTRATION

CO_2 sequestration in geological formations requires proper site selection, effective monitoring, and remediation options should a CO_2 release occur. Much information about subsurface reservoirs has been obtained from oil and gas fields, natural CO_2 reservoirs, and subsurface storage facilities for natural gas and other fluids. The knowledge from these geologic storage examples is extremely valuable (Friedmann, 2007). However, they need to be complemented with additional information, specific to CO_2 properties, to ensure the selection and monitoring of a safe storage site.

Wells for CO_2 sequestration need more demanding specifications

1. Temperature and pressure may be higher under the bottom hole conditions
2. Routine maintenance and repair or replacement of the well equipment may be less acceptable, so, higher integrity in designs expected
3. Well service lives may be longer
4. Leak tolerance during well servicing should be minimum;
5. Integrity should be maintained in every stage of well design and construction, operation, monitoring, work over, suspension and abandonment.

Some areas for additional studies are

1. Geochemical and Petrophysical Studies of the CO_2-Fluid-Rock System
2. Geomechanical Aspects of Injections
3. Basin-Scale Modeling of CO_2 Distribution
4. Isotropic Tagging of Injected CO_2
5. Geophysical methods will play a key role in the monitoring. Developing sensitive and cost effective methods for long-term monitoring is an important part of sequestration.

In Salah Project in Algeria and the Sleipner Project in Norway, the CO_2 that was removed from a natural gas sales stream was being injected into saline aquifers, rather than being vented to the atmosphere. CO_2 enhanced oil recovery in Weyburn project in Canada captured CO_2 from a gasification plant. The West Texas Permian Basin projects relied upon naturally occurring CO_2 from reservoirs (Herzog, 2010; NETL, 2014).

ECONOMIC DECISIONS DEPEND PRIMARILY ON

i. Price of oil
ii. Cost of capital (interest rates) and capital infrastructure construction (drilling, gas processing, pipelines)
iii. Cost of carbon emission taxes, or conversely, the value of carbon sequestration credits
iv. Cost of carbon dioxide capture from anthropogenic sources
v. Pilot project results and
vi. Speed of technology advancement and dissemination

PROPOSED PETROLEUM R&D PROGRAM

i. To Evaluate and enhance carbon dioxide flooding through sweep improvement.
ii. Improve CO_2 flooding sweep using CO_2 gels.
iii. Conduct CO_2 injection tests to improve the reliability of computer simulations of oil fields from CO_2-EOR and calculations of sequestration capacity.
iv. Determine the economic and technical feasibility of using CO_2 miscible flooding to recover oil in a selected oilfield.
v. Employ molecular modeling and experiments to design inexpensive, environmentally benign, CO_2-soluble compounds that can decrease the mobility of CO_2 at reservoir conditions.
vi. Develop a neural network model for CO_2 - EOR.
vii. Develop a novel, low cost method to install geophones for CO_2 monitoring.

MARKET AND PRICE FOR CO_2

CO_2 - EOR production is linked to the price of oil; and rising oil prices have increased the demand for CO_2. The price of CO_2, strongly influenced by regional constraints in supplying CO_2, also increased with rising demand during this period. In the United States alone, the oil and gas industry operates over 13,000 CO_2 - EOR wells, over 3,500 miles of high pressure CO_2 pipelines, has injected over 600 million tons of CO_2 (11 trillion standard cubic feet) and produces about 245,000 barrels of oil per day from CO_2 - EOR projects (Hargrove, 2006).

According to The Energy Information Administration (EIA) (2012) and International Energy Agency (IEA) (2011a),as oil prices will continue to increase over the next decade there will be increasing demand for CO_2 leading to increased CO_2 supplies. In the US the supply of CO_2 is expected to increase by 50 per cent by 2015 relative to

2010 production levels, and could potentially double by 2020 (EIA 2012). More than half this growth will come from A-CO_2 ,which will become increasingly important during the following decade.

The average rate of use of CO_2 in the US is estimated to be 0.5 tonnes of CO_2/barrel of oil in 2011. This is an increase from 0.3–0.4 t CO_2/barrel of oil for some projects as described by earlier studies (Global CCS Institute, 2012). With increasing pipeline investments to relieve supply constraints, together with additional A-CO_2 supply sources being developed, it is expected that over the medium term CO_2 prices will be set by these low-cost anthropogenic sources.

ECONOMIC SUMMARY

Capex: 8% of oil price per barrel;
CO_2 cost: 2.5% of oil price per MCF;
Pay out: 5 years;
IRR: 20%

Cost of CO_2 injection, in general ranging from $60 per ton to higher values based on 2008 data (Jahangiri and Zhang, 2011), depending upon capture process applied, volume of CO_2, distance from source to sink and some other site-specific characteristics."Next generation" CO_2 - EOR technologies, primarily focused on increasing oil production, could create between 165 and 366 Gt of CO_2 storage capacity, while producing 705 to 1,576 billion barrels of incremental oil. Assuming emissions of 6.2 million metric tons/year over 40 years of operation per plant could result in storing the emissions associated with 2,200 to 4,900 one-GW size coal-fired power. This capacity is sufficient to store 18% to 40% of global energy-related CO_2 emissions from 2010 to 2035. "Next generation" CO_2 - EOR technology stores 14% to 18% more CO_2, and produces 47% to 50% more oil than "state-of-the-art" technology. Recent developments in the Permian Basin indicate that there may be vast, previously unrecognized opportunities for additional oil production from the application of CO_2-EOR, besides providing additional capacity for storing CO_2 (US DOE/NETL,2010).

This potential exists in residual oil zones (ROZs) below the oil/water contact in traditional oil reservoirs that are widespread and rich in oil saturation. In addition to the traditional main pay portion of depleted oil fields, they represent a second potentially much larger CO_2 storage option. Field pilots have shown that applying CO_2 - EOR in ROZs appears to be commercially viable. This may result in a two-to-three fold increase in the potential storage capacity associated with the application of CO_2 - EOR.

Other approaches to increase CO_2 storage in conjunction with CO_2 - EOR may further increase storage capacities associated with such applications.

CCS ACTIVITIES IN VARIOUS COUNTRIES

Algeria
A CCS project is in operation (Wright, 2007).

Botswana
Initial assessments on role and opportunity for CCS, undertaking preliminary geologic assessment (Seiphemo, 2014).

Brazil
A Centre of Excellence in CCS R&D has been established. Completed a Geographic Information System (GIS)-based database of CO_2 sources and sinks. Pilot CO_2 injection program underway, reviewing and refining Brazilian Carbon Geological Sequestration Map (CARBMAP) program (Brazil, 2014).

China
CCS has been adopted as a key GHG mitigation technology in National Climate Change Program. Numerous domestic R&D initiatives and efforts are underway to assess and characterize CO_2 storage capacity by Chinese Geological Survey. Several pilot projects for CO_2 capture and CO_2 - EOR, 11 large-scale integrated demonstration projects in the planning stages. (Seligsohn et al., 2010).

Egypt
A study is underway assessing potential for CCS in gas processing and power industry, identifying barriers and environmental impacts(Egypt, 2013).

India
In India, Institute of Reservoir Studies, Oil & Natural Gas Corporation, Ahmedabad, has been carrying out laboratory simulation and pilot scale studies. Western region onland light oilfields have been chosen to be first candidate for the carbon dioxide flooding programme. Under Indo Norwegian collaboration program CSIR-NGRI and SINTEF Petroleum Limited, Norway has carried out reservoir modeling & simulation study for the CO_2 - EOR potential of declining Ankleswar Oil Field, with the support of ONGC. (Dimri et al., 2012).

Indonesia
A study is being finalized on potential for CCS as part of South East Asia CCS Scoping Study, including opportunities for deployment, regulatory and economic analysis. After the assessment of current CCS R&D activities and technical capacity of the domestic industry to provide support throughout the CCS chain, developing a CCS Technology Roadmap for preliminary studies on CCS and EOR (Takahashi, 2015).

Jordan

A study is underway to assess the potential for CCS in oil shale development strategy and to identify and address legal, regulatory, and financial barriers (World Bank. 2012).

Kenya

There is an investigating possibility for high-level storage study.Workshops and training on CCS technology are being conducted (Kenya, 2012).

Kosovo

A study is completled for preliminary geologic potential and capacity-building assessment including legal and regulatory requirements (Kulichenko,N. and Ereira, E., 2011).

Mexico

CCS identified in Special Program on Climate Change and National Energy Strategy 2012–26. Country-level preliminary assessment of CO_2 storage potential completed, pilot projects being considered, including for CO_2 capture with a focus on EOR (McCoy, 2014).

Maghreb

A study is underway to assess the potential for carbon capture on projected and existing power plants in Tunisia, Algeria and Morocco for CO_2 geologic storage and transportation at a regional scale (Kulichenko,N. and Ereira, E., 2011).

Malaysia

Several CCS workshops were conducted for raising awareness and discussing key issues. A study was completed on the long-term role for CCS, opportunities for near-term deployment, technical and financial feasibility, and next steps for further investigation. Capacity-building program developed and activities being implemented (Kulichenko,N. and Ereira, E., 2011).

Norway

Sleipner (Norway) is the world's first successful demonstration of CCS technology into a deep saline reservoir and remains the only development where the CO_2 is both captured and injected offshore. The captured CO_2 is compressed and injected (via one injector well on the Sleipner A platform) into the Utsira Formation, a sandstone reservoir 250 metres / 820 feet thick. The reservoir unit is at a depth of 800-1,100 metres / 2,625-3,610 feet below the seabed. The seal to the reservoir is provided by a 700 metre / 2,430 feet thick gas-tight caprock above the Utsira Formation (Kulichenko,N. and Ereira, E., 2011).

Philippines

A Study is being finalized on potential for CCS as part of South East Asia CCS Scoping Study, including opportunities for deployment, regulatory and economic analysis (Asian Development Bank, 2013).

Saudi Arabia

Has identified CCS as an appropriate low emission technology, Workshops and roundtable discussions were held and sponsored on CCS, including on monitoring and storage specifically, challenges and opportunities. Working towards a EOR-CCS project (Lui et al., 2012).

South Africa

CCS identified as a priority in national White Paper on National Climate Change Response, South African Centre for CCS established, Storage Atlas completed, further basin-specific storage studies underway, scoping study for test injection project being developed. Legal and regulatory review undertaken and further work commenced (Beck et al., 2013).

Thailand

A study being finalized on potential for CCS as part of South East Asia CCS Scoping Study, including opportunities for deployment, regulatory and economic analysis(Asian Development Bank, 2013).

Trinidad and Tobago

CCS Scoping Study, including Legal and Regulatory Review (Kulichenko,N. and Ereira, E., 2011).

United Arab Emirates

Three industrial CCS projects in the planning stages (in the hydrogen, steel, and aluminum industries) (Havercroft, I. et al., 2011).

Vietnam

Study being finalized on potential for CCS as part of South East Asia CCS Scoping Study, including opportunities for deployment and regulatory and economic analysis (Asian Development Bank, 2013).

CONCLUSIONS

1. Carbon dioxide flooding is one of the most attractive processes for enhancing the recovery of oil ,which can also capture part of the carbon dioxide and help in reducing greenhouse gas emission. India should apply this EOR process for its oilfields.
2. Besides laboratory injection studies, investigation of rock and fluid properties of the candidate reservoir with specific studies on wettability, dissolution, precipitation, particle invasion/migration, residual oil saturation on trapped gas saturation, contact time, mass transfer are to be carried out before taking up a pilot project.

3. Finally, the economic viability of any such project should be studied thoroughly before its field application.

ACKNOWLEDGEMENTS

Author expresses his thanks to anonymous reviewer for useful inputs in refining the manuscript.

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