Unconventional energy resources: a system dynamics evaluation of social, environment and economic aspects

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Abstract

This study substantiates the usefulness of a systemic approach to investigate the multi-dimensional challenges regarding environmental, economic, and social impacts facing the sustainable development of unconventional energy resources, particularly oil sands (OS) in Canada. This research uses the system dynamics (SD) methodology to examine the impact of shocks in oil demand using real and theoretical scenarios. This was done by identifying leading indicators critical to OS resource development to capture sustainable development effects. The study identifies the contribution of OS resources in Canada to global sustainable development and has developed a model structure that captures the critical parameters associated with the economic-dynamics, socio-dynamics, and enviro-dynamics for the next 30 years. It also includes the impact of sudden oil supply and demand shocks and presents various recovery scenarios. The results from these scenarios indicate that it may take up to 25 years for the industry to return to its pre-shock trajectory, even assuming a rapid recovery. As such, the study proposes an adaptive model to assist sustainable energy development policies and decision-making. Accordingly, the approach can be helpful for academicians, policymakers, and practitioners for objective decision-making regarding sustainable development. Meanwhile, it provides cogent and valuable information for natural resource governance.

Keywords Oil sands · OS · Sustainable development · Simulation · System dynamics · Oil prices · Canada

Introduction

The depletion of conventional energy resources coupled with volatile energy prices has motivated a shift towards exploration and production of unconventional resources as an alternative energy source. Likewise, the projected increase in global energy demand could inevitably lead to the increased exploitation of unconventional energy sources [19]. Unconventional resources such as the oil sands (OS) could reduce

energy imports, generate employment opportunities, supplement hydrocarbon resource reserves, and ultimately reduce conventional crude prices and demand in the international markets [8, 5]. Conventional resources account for nearly 25%, whereas unconventional resources are estimated to be about 75% of global hydrocarbon resources [19, 27]. Unconventional hydrocarbon resource producers utilize artificial stimuli or unique recovery processes and technologies. The producers extract oil from the OS via surface mining (SM) or in situ extraction processes (IEP). They generally employ SM for OS deposits at about 75 m below surface material (overburden, Bitumen-rich sand, and water-laden muskeg (peat bog) clay. They use IEP for deposits occurring at depths greater than 75 m.

The dissimilarity between conventional and unconventional hydrocarbon resources lies in their mode of occurrence, ease of extraction, and the basins' age in which they occur. Conventional hydrocarbon resources tend to flow from the earth more efficiently, while non-conventional resources are usually more challenging and costlier to extract. Furthermore, conventional resources are characterized by hydrodynamic trapping and unstimulated production, whereas it is

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not the case with unconventional resources. These differences account for the different approaches in their management [29].

Examples of unconventional hydrocarbon resources are shale plays, tight gas, coal-bed methane (CBM), oil shale, OS, and heavy oil. The products such as oil and gas derived from either conventional or unconventional hydrocarbon resources are nearly similar. Stark et al. [34] identify geology, land access and operability, existing unconventional services sector, existing oil and gas distribution networks, competition, and a skilled oil and gas workforce as the critical factors for unconventional resource development.

Bitumen is a highly viscous, soluble biological material that represents a leading resource among OS derivatives. It can be improved to synthetic crude oil (SCO) and processed to create asphalt, gasoline, or jet fuel. Because of its high viscosity, bitumen requires dilution with lighter hydrocarbons to make it transportable by pipelines. These processes were initially very capital intensive; however, recent improvements and technological advances (drilling of horizontal wells and hydraulic fracturing) have made them more profitable and attractive [30, 36]. The SM process requires an average of 2.5 barrels of freshwater to extract one barrel of Bitumen, however, only 0.2 barrels of freshwater are needed by applying the IEP technique. These processes also lead to environmental degradation and the generation of heavy metals such as nickel, vanadium, lead, and mercury [12, 16]. In addition, the greenhouse gas (GHG) emissions related to burning, upgrading, and using OS products are about 10–45% greater than conventional crude oil.

In the long run, OS's entire development process strains the local communities, the nationwide environment, and, eventually, the globe. Examples of associated environmental effects of this development include an increased concentration of hydrogen sulphide in the air; reduction in some wildlife species; host community exposure to environmental risks including air and water contamination, and land displacement; loss of habitats and wetlands; mass death of waterfowl in tailings ponds; toxin accumulations and climate change [10, 20, 37, 40].

Most of the global OS reserves are in Alberta (Canada) and Venezuela, sharing an estimated 4 trillion barrels of oil, almost half of the worldwide estimate at about 8–9 trillion barrels [7,

37]. OS resources are prominent in Canada, Venezuela, and also Nigeria. In Canada, commercial production started in the 1960s and has continually been rising due to technological advancement [36]. At present, there are more than 20 active mining and in situ OS projects, with most industry activity centred on the Athabasca area [30]. Canada possesses ample human resources, a stable political system, a well-developed infrastructure, a robust monetary system, and an established monitoring system. All these contribute meaningfully to Canada's OS industry [22]. Also, employment creation and revenues from taxes and royalties are some of the added benefits [5]. Nevertheless, the SM process of extracting Athabasca OS has its attendant environmental degradation [38].

Venezuela is a significant contributor to global oil reserves. OS reserves of Venezuela occur in similar reservoir types as seen in Canada; thus, they share geo-mechanical and petro-physical properties and produce a similar heavy crude. However, Venezuela is a member of the “Organization of Petroleum Exporting Countries”, while Canada is not, with a current crude oil production of 303,806 mbl [27]. However, the industry in Venezuela is affected by environmental impacts on water, land, air, inadequate technology, underinvestment in exploration, and political-economic inefficiencies compared to its Canadian counterpart [22].

The unexploited OS of Nigeria can potentially generate at least 43 bbl of crude oil. This resource displays characteristics that compare favourably with OS in Canada. The exploitation could result in industrial and commercial advantages for the nation and the international community; however, this is not without potential challenges [2, 12, 16, 24, 26]. Table 1 summarizes the developmental history, estimates, and OS contribution.

Sustainable development of unconventional resources poses a tremendous challenge for societies, governments, and transnational organizations. This quest for sustainable development has resulted in the setting up of organizations and institutions, such as the “Environmental Protection Agency” (EPA), “Organization for Economic Cooperation and Development” (OECD), and “United Nations Sustainable Development Goals” (UN SDGs) [14]. These organizations have put forward functional gauges for monitoring and assessing sustainable development status [11]. A universally accepted

Table 1 Comparison of Canada, Venezuela, and Nigeria Oil Resource in billion barrels (bbl) [9, 27, 28]

Countries	Proven Crude Oil reserves (bbl)	Development History	Production Estimates (bbl)	OS Contribution
Venezuela	298.4	Significant development commenced in 2000	24.7	220 bbl is from OS
*Canada	173.0	Commercial development started in the 1960s	Not Applicable	168 bbl is from OS
Nigeria	37.1	Yet to commence	3.1	Presently no contribution from OS

*Canada is a Non-OPEC Country

definition for sustainable development, “the development of natural resources to provide for the present's needs without endangering or hampering the capacity of upcoming generations to cater to their requirements”. This definition has three perspectives: environmental, economic, and socially sustainable development [32].

Resource development, inadvertently, results in complex and multi-dimensional environmental, economic, and social impacts. For example, OS reserves consist of sand, water, a collection of minerals, and bitumen. Exploration and development of this resource represent a national and global concern. Many authors focus on the sustainable development of this reserve because of the concurrent impacts on the “economic, social, and environmental” perspectives of sustainable development [11, 13, 17, 32]. The impact on terrestrial and aquatic pressure, safety, sea and land contamination, hothouse gas releases, and dislodgment of inhabitants from contiguous societies requires a comprehensive approach, thus motivating this current study. This resource development affects the environment, eco-system, communities, with repercussions for sustainable development, and there is a need for a systemic approach to resource exploitation, hence this study. This study takes into consideration the interactions and reverberating effects of various elements constituting the OS resource system.

Spaiser et al. [33] argue that there exists inconsistency between economic growth and sustainable development. Their findings show that “while economic growth fulfils the socio-economic goals, it could hamper the environmental goals”. They perceive sustainable development as a long-term process with unexpected changes in the future. The changes could include technological innovations. Researchers [23] observed from their study that economic growth often results in environmental deterioration in the short run. Successful mitigation of mismatch (“economic development and environmental sustainability”) requires identifying the prohibiting factors to sustainable development, using data analyses and other approaches [33].

This study presents the examination of the possible consequences of OS development on sustainability in the Canadian context. It explores the three-dimensional effects: enviro-dynamics, economic-dynamics, and socio-dynamics of exploiting the OS resource on sustainability. The investigation uses the system dynamics (SD) methodology to generate OS extraction scenarios, alongside attendant economic, social, and environmental implications. The study aims to:

- (a) identify the impact of OS production in Canada on sustainable development,
- (b) examine the interaction among the environmental, economic, and social dimensions as a system and thus propose potentially effective ways to attain sustainable development, and

- (c) explore the impact of fluctuations in oil prices created by demand and supply shocks.

Methodology—a model structure

System dynamics methodology

We have employed a computer simulation technique called SD to explore the nonlinear trends in OS production and the associated factors from three sustainable development perspectives: environmental (enviro-dynamics), economic (economic-dynamics), and social (socio-dynamics). Forrester [15] and Sterman [35] described SD methodology as a blend of traditional management with scientific feedback control.

SD enables an understanding of the observed dynamics of interest, how and why they occur. The dynamics help to formulate appropriate managerial policies to improve the situation. It often utilizes an influence diagram that describes the dynamics and causality relationships existing among variables in a system under study. In the terminology of SD, a model consists of interconnected stocks, flows, and converters. Modellers generally use a special-purpose software package that sets up a system of first-order differential equations with boundary conditions that are then solved by the software using numerical methods. We built scenarios to analyse the repercussions on global sustainable development and reconnoitre interactions amid OS extraction and sustainable development. The SD simulation was then utilized to examine changes over a specified duration using a time-step approach.

First, a cause-and-effect model was developed, showing where we are today regarding oil extracted from the Canadian OS, how we got here, and potential alternative futures under various scenarios. We built the model in the Vensim (www.vensim.com) and Stella Professional (www.iseesystems.com) software packages based on information obtained in the OS Factbook [4]. Next, this model was converted to MS Excel [3] to be validated, and we estimated the parameters of the model by minimizing the sum of squared error between the time-series data provided by the Canadian Association of Petroleum Producers (CAPP) GHG Emissions [31] and the model's results.

Some significant variables and cardinal sustainable development indicators identified as relevant to this study [13, 18, 22, 23, 30, 31] include the following: *economic-dynamics*: employment, GDP; *enviro-dynamics*: land use, water use, GHG (CO₂) emissions, heavy metal emission; *socio-dynamics*: displacement, infrastructure, public services, and farming/fishing.

Model description

This section shows the Vensim (Decision Support System for Windows Version 11. A Double Precision) software version. Annexure 1 lists the nomenclature used in the model.

Figure 1i shows an overview of the system dynamics model, which shows the six sub-models and how they are connected. Figure 1ii shows a mid-level view of the system dynamics model of the Canadian case showing some of the critical internal workings of the sub-models. The model contains OS extraction influenced by the workforce and their productivity, the required use of land and water, and the emissions produced. The emissions affect the First Nations people living in the area, which affects their social well-being. Land

use affects wildlife, and water use affects fish. The wildlife, fish, and emissions are aspects of environmental well-being. Finally, OS production provides royalties, taxes, and wages that influence the country's economic well-being.

Figure 2i shows the Vensim diagram for the oil extraction model. Oil is extracted from the reserves using mining and drilling. We calculate the rate of extraction based on the workforce and their productivity. This portion of the model was validated using data from 2010 to 2020 [6]. Figure 2ii shows the workforce model. There is an initial workforce in 2010, and a long-term planned workforce is based on the time to “hire” or “fire” workers. The planned workforce is adjusted when the industry is profitable. If there are profits, the hiring will continue towards the planned level. However,

Fig. 1 (i). Model overview (Authors' view). (ii). Mid-level model view (Authors' view)

(i). Model Overview (Authors' view)

(ii). Mid-Level Model View (Authors' view)

(i). Oil Extraction Model

(ii). Workforce Model

(iii). Productivity Model

Fig. 2 (i) Oil extraction model. (ii) Workforce model. (iii) Productivity model

if there are no profits, there will be lay-offs until the profits return. Profits are calculated based on the break-even price of mining and drilling. When the price is above the break-even price, there will be profits and hiring. When the price is below the break-even price, there will be losses and lay-offs. Figure 2iii displays the productivity model. This model provides values for the productivity (in barrels/person/year) overtime used in the oil extraction model shown in Fig. 2i. This model has initial productivity, long-term productivity, and a time to change productivity.

The First Nations' population model, shown in Fig. 3, is an exploratory model that was not validated. We use a classic population model with birth and departure rates, including deaths and emigration. The emissions created by OS mining and drilling affect the departure time so that more people will depart the reserve, the higher the emissions per year [21].

Figure 4 shows an exploratory model of social well-being based on the services and infrastructure provided by the oil industry to workers and the First Nations people. Profits influence the investment in services and infrastructure. If there are

profits, there is an investment in services and infrastructure, but there is no investment in services and infrastructure if there are losses. We estimate the social well-being by comparing the services and infrastructure provided per person, divided by the initial services and infrastructure provided per person. Although this is an exploratory model, it is reasonably robust to parameter changes.

Figure 5 shows an exploratory model of economic well-being based on the royalties and taxes paid by the oil industry on their profits. We calculate the profits based on the oil price and the break-even costs for mining and drilling. Economic benefits also include wages paid to workers in the industry. We estimate the economic well-being by comparing the estimated economic benefits per year, divided by the initial economic benefits.

The environment model is in Fig. 6. In the model, we assume that the investment in research and development depends on profits. When there are profits, there is the possibility of investment in research and development to reduce emissions. When there are losses, there will be a limited

Fig. 3 First Nations population model

Fig. 4 Social well-being model

We developed exploratory models demonstrating the influence of land use on wildlife and water use on fish in Fig. 7. Figure 8 shows the environmental well-being model.

Results and discussion

Significant parts of the OS model were validated using the data provided in [6, 25]. The results presented utilize the best available information about Government of Canada initiatives for pipeline construction and environmental policies that may impact oil extraction from the OS.

Figure 9 shows the dataset from [6] labelled “actual” for total and projected OS extraction compared to the model's results. We obtained the fit by modifying the workforce's size and productivity to minimize the squared error between the

actual and model values. Discontinuities in the data resulted from comparing historical prices of oil and the break-even prices for extraction by mining and drilling. After the supply and demand shock, it is projected that oil extraction will grow again. The growth rate from 2012 to 2018 ranged from 8 to 14%. Then, the drop in prices starting in 2019 resulted in an 8% contraction rate. Although Canada's Energy Regulator projects a rapid recovery in 2021 for 10% growth, our model is slightly less optimistic and expects a more gradual increase in oil extraction from 2021 to 2025. Various environmental policies to reduce CO₂ emissions over the next 30 years will

Fig. 7 Wildlife and fish model

Fig. 8 Environmental well-being model

Fig. 9 Data and projections from [6] compared to model oil extraction

impact the oil extraction growth rate. Canada's Energy Regulator estimates a growth rate between 1 and 3% reaching a peak in 2039 and then beginning a gradual decline by about 1% a year [6].

Also, Canada's Energy Regulator [6] provides a projection for the emissions per barrel created by mining and drilling. Figure 10 shows the fit of the time-series data and the model projection for the emissions per barrel from mining. Canada's Energy Regulator expects the emission rates to decline by 1 to 2% per year over the next 30 years through improvements in the extraction processes. By fitting the data, we were able to estimate the parameters of our model. We found the water use parameters in [25] and the land-use parameters in “Past and Future Land Use Impacts of Canadian OS and Green House Gas Emissions”. Therefore, we consider the model to be partially validated and partially exploratory.

Two scenarios were considered based on combinations of high and low break-even prices for mining and drilling and a high or low oil price. The break-even price of oil for mining to be profitable is between \$75 and \$85 USD per barrel. The

break-even price of oil for drilling to be profitable is between \$50 and \$60 USD per barrel. We obtained the historical price of oil and the projected future price of oil from [6]. The projected values were varied by increasing or decreasing the expected value by 20% to consider the uncertainty in the oil price in the future (see Fig. 11).

Figure 12 shows the future annual profits and losses for mining and drilling based on different break-even prices and comparative oil prices. It appears the OS will remain profitable if oil prices remain high. However, it may suffer continuing losses if costs stay reasonably high and prices remain low into the future. If prices remain low and extraction costs stay high, the industry will be only marginally profitable or may even lose money. Figures 13, 14, 15 and 16 show the social, economic, and environmental well-being based on combinations of high and low production costs and oil prices. Profit is the driving force in the dynamics of economic, social, and environmental well-being. The industry will not be sustainable if production costs are high and prices remain low, but this would be good for environmental well-being, whereas

Fig. 10 Data and projections from [6] compared to model emissions mining

Fig. 11 Price per barrel

Fig. 12 Annual profit **Fig. 13** Well-being with low prices and low costs

the situation would reverse if prices increase above the break-even levels. Therefore, a trade-off needs to be recognized.

The social, economic, and environmental impacts of OS over 40 years compared to 2010 values using the SD model and an examination of various recovery situations after the supply and demand shocks that have led to low oil prices. This has resulted in the following observations: Oil production was increasing at a rate of between 8 and 14% before the supply and demand shocks, however the shocks resulted in an 8% reduction in oil production between 2019 and 2020. Furthermore, from our findings, projections now show a rapid growth in oil production of about 10% in 2021. We also discover that, as a result of the coming into effect of new environmental policies to control CO₂ emissions, emissions from oil extraction in the OS will continue to decrease by somewhere between 0.5 and 2% per year for the next 30 years. Whereas

oil production will reduce to 3% or less, it will peak around 2039, this will be followed by a decline of 1% a year.

This study also discovered that the economic, social, and environmental well-being values are currently around the 2010 levels. The results obtained are highly sensitive to future oil prices, such that if oil prices remain lower than the break-even prices of mining and drilling, the industry will not be viable in the long run. On the contrary, if oil prices return to levels above the break-even prices of mining and drilling, economic and social well-being will improve substantially, but we expect economic well-being to reach a near-equilibrium around 2050 as mining and drilling peak. Since international oil prices are beyond the industry's control, investing in technologies that improve worker productivity and decrease extraction costs is crucial. We also observed that if the industry remains viable, the environmental well-being will remain

Fig. 14 Well-being with low prices and high costs **Fig. 15** Well-being with high prices and low costs

below its 2010 value for the foreseeable future. It is an open question whether the potential for future OS social and economic benefits will offset the environmental costs even with currently planned policies to reduce CO₂ emissions.

There has been protracted economic dependence on the vast oil reserves of Canadian OS. However, the coronavirus downturn decimated demand for OS oil, leading to the shedding of jobs [39]. Likewise, lockdown and curfew measures to curb the spread have sharply reduced global energy demand, thus creating a demand shock [1]. It is difficult to predict how the OS industry will recover after the demand shock created by the COVID-19 pandemic. This study examined four scenarios based on the projected oil prices and a range of break-even prices. Oil prices would need to regain

previous highs, and extraction costs remain relatively low for the industry to be economically viable.

After this detailed examination of the environmental, economic, and social impacts of the OS in Canada, it appears there is a significant trade-off. Water and land use and GHG emissions result in a negative environmental impact. However, technological advances in reclaiming land, recycling water, and reducing emissions may soften these environmental impacts.

In our study, the social effects focused on First Nations people. Improvements in infrastructure and social services for First Nations people seem to be creating a highly positive influence. Although not explicitly modelled, we realize that negotiations with First Nations people on the use

Fig. 16 Well-being with high prices and high costs

of treaty land will need to be sensitive to the long history of broken promises and harsh effects created by past efforts to assimilate First Nations people. The First Nations people have a solid connection to the land, wildlife, and fish. So although OS developers may compensate First Nations people socially and economically, the industry will have to guarantee that the land and water resources are protected to the First Nations' satisfaction if the industry wants to avoid conflicts and disruptions.

Economically, OS is a significant source of tax revenue and royalties paid to the federal and provincial governments that benefit all Canadians and Albertans, in particular. In addition, the OS creates a significant number of highly skilled and well-paying direct and indirect jobs. Therefore, it appears that if technological advances continue to reclaim land, recycle water, and reduce emissions while also increasing productivity, the OS drilling can be developed sustainably, thereby providing significant social and economic benefits to Canada. On the other hand, OS mining incurs higher costs both financially and environmentally. Therefore, there appears to be some uncertainty about the sustainability of OS mining.

Conclusion

This study explores the implications of OS resource development and the extraction of global sustainable development. This was done by studying OS extraction and development in Canada. To achieve this, major indicators for assessing sustainable development, developed by international organizations such as the OECD and UNSDGs, were examined. We identified leading indicators critical to OS resource development to capture sustainable development effects.

We investigated the contribution of OS resources to global sustainable development and the significant environmental, social, and economic domains. We observed that for OS extraction to culminate in sustainable development over the next 30 years, there is the need for a mutual and voluntary trade-off, especially in the displacement of residents in the OS extraction area. There is also the need for technology improvements to reduce GHG emissions and water pollution.

We used an SD approach to develop a model structure that captures critical sustainable development indicators associated with economic, social, and environmental dimensions.

Future work on this system dynamics model would consider:

- (1) The fact that land, water, hunting, and fishing impact First Nations' social well-being, and these, in turn, will affect their acceptance or rejection of pipeline construction and, therefore, the shipping of oil and the profitability of the industry, and
- (2) Include the adaptation of this model to OS development in Venezuela and Nigeria and assess their implications on global sustainable development.

Declaration

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this submission.

Software

1. www.vensim.com, 2. www.iseesystems.com

Annexure 1: Nomenclature used in the model

Name	Units	Type	Model
AVERAGE PRICE	dollars/barrel	Constant	Economic Well-Being
AVERAGE WAGE	(dollars/person)/year	Constant	Economic Well-Being
BIRTH RATE	(people/person)/year	Constant	Social Well-Being
Births	people/year	Flow	Social Well-Being
Change in driller productivity	((barrels/person)/year)/year	Flow	Productivity
Change in emission rate drilling	(kg/barrels)/year	Flow	Environmental Well-Being
Change in emission rate mining	(kg/barrels)/year	Flow	Environmental Well-Being
Change in services	service units/year	Flow	Social Well-Being
COVID START TIME	years	Constant	Workforce
COVID DESIRED WORKFORCE	people	Constant	Workforce
COVID DURATION	years	Constant	Workforce
Departures	people/year	Flow	Social Well-Being
Desired drilling workforce	people	Auxiliary	Workforce
Departure time	years	Auxiliary	Social Well-Being
DESIRED EMISSION RATE DRILLING	kg/barrels	Constant	Environmental Well-Being
DESIRED EMISSION RATE MINING	kg/barrels	Constant	Environmental Well-Being
Desired services	service units	Auxiliary	Social Well-Being
Domestic pipeline	barrels/year	Flow	Oil Extraction
Domestic rail	barrels/year	Flow	Oil Extraction

Name	Units	Type	Model
Driller Productivity	(barrels/person)/year	Stock	Productivity
Drilling	barrels/year	Flow	Oil Extraction
Drilling Oil Reserves	barrels	Stock	Oil Extraction
Drilling Workforce	people	Stock	Workforce
Economic benefits	dollars/year	Auxiliary	Economic Well-Being
Economic well-being	dimensionless	Auxiliary	Economic Well-Being
EFFECT OF EMISSIONS ON DEPARTURE TIME	dimensionless	Look-up table	Social Well-Being
EFFECT OF LAND AVAILABLE ON WILDLIFE LIFE EXPECTANCY	dimensionless	Look-up table	Environmental Well-Being
Emission Rate Drilling	kg/barrels	Stock	Environmental Well-Being
Emission Rate Mining	kg/barrels	Stock	Environmental Well-Being
Emissions	kg/year	Auxiliary	Environmental Well-Being
Dimensionless	dimensionless	Auxiliary	Environmental Well-Being
Exports pipeline	barrels/year	Flow	Oil Extraction
Exports rail	barrels/year	Flow	Oil Extraction
Extracted Oil	barrels	Stock	Oil Extraction
Extraction	barrels/year	Auxiliary	Oil Extraction
First Nations People	people	Stock	Social Well-Being
Fish	fish	Stock	Environmental Well-Being
FRACTION DOMESTIC	fraction	Constant	Oil Extraction
Hiring or firing drillers	people/year	Flow	Workforce
Hunting	wildlife/year	Flow	Environmental Well-Being
HUNTING RATE	(wildlife/wildlife)/year	Constant	Environmental Well-Being
Initial total population	people	Auxiliary	Social Well-Being
Initial workforce	people	Auxiliary	Workforce
INITIAL DRILLER PRODUCTIVITY	(barrels/person)/year	Constant	Productivity
INITIAL DRILLING WORKFORCE	people	Constant	Workforce
Initial economic benefits	dollars/year	Auxiliary	Economic Well-Being

Name	Units	Type	Model	Name	Units	Type	Model
INITIAL EMIS- SION RATE DRILLING	kg/barrels	Constant	Environmental Well-Being	Net water use	barrels/year	Flow	Environmental Well-Being
INITIAL EMIS- SION RATE MINING	kg/barrels	Constant	Environmental Well-Being	NORMAL DEPARTURE TIME	years	Constant	Social Well- Being
Initial emissions	kg/year	Auxiliary	Environmental Well-Being	NORMAL WILDLIFE LIFE EXPEC- TANCY	years	Constant	Environmental Well-Being
INITIAL EXTRACTED OIL	barrels	Constant	Oil Extraction	Pipeline Produc- tivity	(barrels/per- son)/year	Stock	Productivity
INITIAL FIRST NATIONS PEOPLE	people	Constant	Social Well- Being	Pipeline Work- force	people	Stock	
INITIAL FISH	fish	Constant	Environmental Well-Being	Rail Productivity	(barrels/per- son)/year	Stock	Productivity
INITIAL LAND AVAILABLE	km ²	Constant	Environmental Well-Being	Rail Workforce	people	Stock	
INITIAL LAND USED	km ²	Constant	Environmental Well-Being	RECLAMA- TION RATE	(km ² /km ²)/ year	Constant	Environmental Well-Being
INITIAL SER- VICES	service units	Constant	Social Well- Being	RECYCLING RATE DRILL- ING	fraction	Constant	Environmental Well-Being
INITIAL WATER AVAILABLE	barrels	Constant	Environmental Well-Being	RECYCLING RATE MIN- ING	fraction	Constant	Environmental Well-Being
INITIAL WATER USED	barrels	Constant	Environmental Well-Being	ROYALTY RATE	dollars/barrels	Constant	Economic Well- Being
INITIAL WILD- LIFE	wildlife	Constant		Royalties	dollars/year	Auxiliary	Economic Well- Being
Land Available	km ²	Stock	Environmental Well-Being	Services	service units	Stock	Social Well- Being
LAND USE RATE DRILL- ING	km ² /barrels	Constant	Environmental Well-Being	Services density	people/service units	Auxiliary	Social Well- Being
LAND USE RATE MIN- ING	km ² /barrels	Constant	Environmental Well-Being	SHIPPING TO DOMESTIC REFINERIES	million barrels/ day	Constant	Oil Extraction
Land Used	km ²	Stock	Environmental Well-Being	Social well- being	dimensionless	Auxiliary	Social Well- Being
LONG-TERM DRILLER PRODUCTIV- ITY	(barrels/per- son)/year	Constant	Productivity	TAX RATE	dollars/barrels	Constant	Economic Well- Being
LONG-TERM DRILLING WORKFORCE	people	Constant	Workforce	Taxes	dollars/year		Economic Well- Being
Miner Produc- tivity	(barrels/per- son)/year	Stock	Productivity	TIME TO CHANGE DRILLER PRODUCTIV- ITY	years	Constant	Productivity
Mining	barrels/year	Flow	Oil Extraction	TIME TO CHANGE EMISSION RATE DRILL- ING	years	Constant	Environmental Well-Being
Mining Oil Reserves	barrels	Stock	Oil Extraction	TIME TO CHANGE EMISSION RATE MIN- ING	years	Constant	Environmental Well-Being
Mining Work- force	people	Stock	Workforce				
Net land use	Km ² /year	Flow	Environmental Well-Being

Name	Units	Type	Model
TIME TO CHANGE SERVICES	years	Constant	Social Well-Being
TIME TO HIRE OR FIRE DRILLERS	years	Constant	Workforce
Total pipeline	barrels/year	Auxiliary	Oil Extraction
Total population	people	Auxiliary	Social Well-Being
Total rail	barrels/year	Auxiliary	Oil Extraction
TOTAL SHIP-PING	million barrels/day	Constant	Oil Extraction
Total workforce	people	Auxiliary	Workforce
Wages	dollars/year	Auxiliary	Economic Well-Being
Water Available	barrels	Stock	Environmental Well-Being
WATER USE RATE DRILLING	barrels/barrels	Constant	Environmental Well-Being
WATER USE RATE MINING	barrels/barrels	Constant	Environmental Well-Being
Water Used	barrels	Stock	Environmental Well-Being
Wildlife	wildlife	Stock	Environmental Well-Being
WILDLIFE BIRTH RATE	(wildlife/wildlife)/year	Constant	Environmental Well-Being
Wildlife births	wildlife/year	Flow	Environmental Well-Being
Wildlife deaths	wildlife/year	Flow	Environmental Well-Being
Wildlife life expectancy	years	Auxiliary	Environmental Well-Being

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Availability of data and material Significant parts of the OS model were validated using the data provided in the “Canadian Energy Regulator's report” [6], the Natural Resources Canada “Energy Fact Book 2020–2021” [25], and “Canada's Energy Future 2020”. All sources of data are listed under Reference section.

Code availability The SD model developed and resulting scenarios are available at the link: <https://github.com/ivanwtaylor/Oil-Sands>.

References

1. A Vision for Canada's Recovery Canada's Natural Gas and Oil Industry: Driving Economic Recovery and Environmental Leadership 2020 [Internet]. CAPP.ca. [cited 12 July 2021]. Available from: <https://www.capp.ca/wp-content/uploads/2020/09/A-Vision-for-Canadas-Recovery-375388-1.pdf>
2. Agbor A (2010) Bitumen mining and exploration: the prospects and challenges in Ode-Irele, Irele local government, Ondo state Nigeria [Internet]. Academia.edu. 2010 [cited 2 August 2021]. Available from: <https://www.academia.edu/36543384/>
3. Albright, S.C.: VBA for Modelers: Developing Decision Support Systems with Microsoft Excel, 4th edn. Cengage Learning, Boston (2011)
4. Canadian Association of Petroleum Producers (CAPP) (2021) Canada's OS, Calgary, Alberta, Canada. Oil Sands procurement from indigenous suppliers increases to \$2.4 billion. [cited 2 August 2021]. <https://www.capp.ca/news-releases/oil-sands-procurement-from-indigenous-suppliers-increases-to-2-4-billion/>
5. Canadian Energy Research Institute (CERI) (2014) [cited 10 August 2021]. Available from: http://www.ceri.ca/images/stories/CDN_Economic_Impacts_of_New_and_Existing_Oil_Sands_Development_in_Alberta_-_November_2014_-_Final.pdf
6. Canada's Energy Regulator (CER) (2020) Cer-rec.gc.ca. [cited 27 August 2021]. Available from: <https://www.cer-rec.gc.ca/en/data-analysis/canada-energy-future/2020/index.html>
7. Canada's sustainability progress held back by eco issues [Internet]. Canadian Geography Canadian Association of Petroleum Producers, (CAPP). (2008) [cited 20 August 2021]. Available from: <https://www.canadiangeographic.ca/article/canadas-sustainability-progress-held-back-eco-issues>
8. Compagnie Générale de Géophysique (CGG) (2014) [cited 4 July 2021]. Available from: <https://www.cgg.com/en/What-We-Do/Your-Challenges/Unconventional-Resources>
9. Dusseault MB (2001) Comparing Venezuelan and Canadian heavy oil and tar sands. In: Canadian International Petroleum Conference. Petroleum Society of Canada.
10. Environmental Impacts of Oil Sands Development in Alberta - Resilience [Internet]. Resilience. 2009 [cited 13 August 2021]. Available from: <https://www.resilience.org/stories/2009-09-22/environmental-impacts-oil-sands-development-alberta/>
11. Falebita, O., Koul, S.: From developing to sustainable economy: A comparative assessment of India and Nigeria. *Environ Develop* **25**, 130–137 (2018)
12. Falebita O (2014) The Nigerian tar sands: a techno-economic analysis. LAP LAMBERT Academic Publishing.
13. Falebita, O.A., Koul, S., Akinbami, J.F., Akarakiri, J.B.: Sustainable resource management: a societal uncertainty perspective. *Int J Sust Dev World* **27**(2), 167–178 (2020)
14. Framework and suggested indicators to measure sustainable development. UNECE.org. 2013 [cited 24 August 2021]. Available from: http://www.unece.org/fileadmin/DAM/stats/documents/ece/ces/2013/SD_framework_and_indicators_final.pdf
15. Forrester, J.W.: Urban dynamics. MIT, Cambridge (1969)
16. Geotechnical Investigations of the Ondo State Bituminous Sands. NG.BOELL, (1980) [cited 12 August 2021]. Available from NG.boell.org: https://ng.boell.org/sites/default/files/bitumen_in_nigeria.pdf
17. Harris JM (2000) Basic principles of sustainable development (G-DAE Working Paper No. 00-04). Medford, MA: Tufts University, The Global Development and Environmental Institute
18. Heyes, A., Leach, A., Mason, C.F.: The economics of Canadian oil sands. *Rev Environ Econom Policy*. **12**(2), 242–263 (2018)
19. International Energy Agency (IEA) (2019) Executive Summary. In: *World Energy Outlook*. OECD, 23–28.
20. Jordaan SM (2011) Governance of impacts to land and water resources from OS development in Alberta. ILAR, Working Paper #3 Available from: <https://ilar.ucsd.edu/publications/index.html>
21. Leahy S (2019) Alberta, Canada's oil sands is the world's most destructive oil operation—and it's growing [Internet].

- Environment. [cited 13 August 2021]. Available from: <https://www.nationalgeographic.com/environment/2019/04/alberta-canadas-tar-sands-is-growing-but-indigenous-people-fight-back/>
22. Liu, Z., Wang, H., Blackburn, G., Ma, F., He, Z., Wen, Z., Wang, Z., Yang, Z., Luan, T., Wu, Z.: Heavy oils and oil sands: Global distribution and resource assessment. *Acta Geologica Sinica - Engl Ed.* **93**(1), 199–212 (2019)
 23. Massa-Sánchez, P., Quintana-Romero, L., Correa-Quezada, R., del Río-Rama, M.D.: Empirical evidence in Ecuador between economic growth and environmental deterioration. *Sustainability.* **12**(3), 853 (2020)
 24. Ministry of Solid Minerals Development (MSMD) (2006) Technical Overview; Nigeria's Bitumen Belt and Development Potential: 27–32
 25. Natural Resources Canada (NRCan) [Internet]. Nrcan.gc.ca. 2020 [cited 15 Sept 2021]. Available from: https://www.nrcan.gc.ca/sites/nrcan/files/energy/energy_fact/energy-factbook-2020-2021-English.pdf
 26. Olatumile, A.: Assessment of Development Indices in Nigeria's Bitumen Communities. *Mediterranean. J Soc Sci* **3**(3), 381–385 (2012)
 27. OPEC Share of World Crude Oil Reserves (2014). In Annual Statistical Bulletin. [cited 24 July 2021]. Available from: http://www.opec.org/opec_web/en/publications/202.html
 28. OPEC Annual Statistical Bulletin [Internet]. Asb.opec.org. 2020 [cited 25 August 2021]. Available from: https://asb.opec.org/ASB_PDFDownload.php
 29. Peacock, D.: Unconventional reserves and resources in the Petroleum Resource Management System (PRMS): a square peg in a round hole? *APPEA J* **54**(2), 518 (2014)
 30. Poveda, C.A.: The Canadian oil sands development: Management of land, air and water resources. *Eur J Sustain Develop* **4**(2), 359–368 (2015)
 31. Reclaiming Land, Water Use, GHG Emissions [Internet] (2015) Canadian Association of Petroleum Producers (CAPP). [cited 12 August 2021]. Available from: <http://www.oilsandstoday.ca/topics>
 32. Robert KW, Parris TM, Leiserowitz AA (2005) What is sustainable development? Goals, indicators, values, and practice. *Environ Sci Policy Sustain Develop* **47**(3):8–21
 33. Spaier, V., Ranganathan, S., Swain, R.B., Sumpter, D.J.: The sustainable development oxymoron: quantifying and modelling the incompatibility of sustainable development goals. *Int J Sust Dev World* **24**(6), 457–470 (2017)
 34. Stark M, Zhao S, Pereira P, Heyes N, Deng D, Blanco F, Chudziak J, David M, Nouwailati K, Kornelius, S (2021) Integrating Unconventionals International Development of Unconventional Resources: If, where and how fast? Accenture.com. [cited 4-Sept 2021]. Available from: <http://www.accenture.com/SiteCollectionDocuments/PDF/AccentureEnergy-International>
 35. Sterman, J.: Business dynamics. Systems thinking and modeling for a complex world. Irwin/McGraw-Hill, Boston (2000)
 36. Tailing management assessment Report: OS Mining Industry, Calgary, Alberta: Energy Resources Conservation Board (ERCB). Osipfiles.alberta.ca. 2013 [cited 20 August 2021]. Available from: http://osipfiles.alberta.ca/datasets/158/Tailings_ManagementAssessmentReport2011-2012.pdf
 37. U.S. Energy Information Administration (EIA) [Internet]. Eia.gov. [cited 4-August 2021]. Available from: <http://www.eia.gov/naturalgas/data.cfm>.
 38. Water Usage [Internet]. Oilsandsmagazine.com. Oil Sands Magazine; 2016 [cited 20 August 2021]. Available from: <https://www.oilsandsmagazine.com/technical/environment/water-usage>
 39. Williams C (2020) As Oil Industry Swoons, Tar Sands Workers Look to Renewables for Jobs 2020 [Internet]. *Yale E360*. [cited 25 July 2021]. Available from: <https://e360.yale.edu/features/as-oil-industry-swoons-tar-sands-workers-look-to-renewables-for-jobs>
 40. Yeh S, Zhao A, Hogan SD, Brandt AR, Englander JG, Beilman DW, Wang MQ (2015) Past and future land use impacts of Canadian oil sands and greenhouse gas emissions. Davis, CA, USA: UCD-ITS-RR-15–01 Institute of Transportation Studies, University of California.

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