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, under-investment 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,
(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 layoffs. 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
investment in research and development to reduce emissions. By multiplying these values by the amount of drilling and mining each year, we estimated the total emissions per year from oil extraction.

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

Oil Extraction

- Actual Extraction
- Model 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

![Emissions per Barrel Mining](image-url)

Fig. 11 Price per barrel

![Price Sensitivity](image-url)
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...
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...
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.

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       |
|-----------------------------|------------------------|--------------------|-------------|
| Driller Productivity        | (barrels/person/year)  | Stock              | Productivity|
| Drilling Oil Reserves       | barrels/year           | Flow               | 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 |
| 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 |
| 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 DRILLING 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                  |
|-------------------------------------------|------------------------|-----------------|------------------------|
| INITIAL EMISSION RATE DRILLING            | kg/barrels             | Constant        | Environmental Well-Being |
| INITIAL EMISSION RATE MINING              | kg/barrels             | Constant        | Environmental Well-Being |
| Initial emissions                         | kg/year                | Auxiliary       | Environmental Well-Being |
| INITIAL EXTRACTED OIL                     | barrels                | Constant        | Oil Extraction         |
| INITIAL FIRST NATIONS PEOPLE              | people                 | Constant        | Social Well-Being      |
| INITIAL FISH                              | fish                   | Constant        | Environmental Well-Being |
| INITIAL LAND AVAILABLE                    | km2                    | Constant        | Environmental Well-Being |
| INITIAL LAND USED                         | km2                    | Constant        | Environmental Well-Being |
| INITIAL SERVICES                          | service units          | Constant        | Social Well-Being      |
| INITIAL WATER AVAILABLE                   | barrels                | Constant        | Environmental Well-Being |
| INITIAL WATER USED                        | barrels                | Constant        | Environmental Well-Being |
| INITIAL WILDLIFE                          | wildlife               | Constant        | Environmental Well-Being |
| Land Available                            | km2                    | Stock           | Environmental Well-Being |
| LAND USE RATE DRILLING                    | km2/km2/barrels       | Constant        | Environmental Well-Being |
| LAND USE RATE MINING                      | km2/km2/barrels       | Constant        | Environmental Well-Being |
| Land Used                                 | km2                    | Stock           | Environmental Well-Being |
| LONG-TERM DRILLER PRODUCTIVITY            | (barrels/person)/year | Constant        | Productivity           |
| LONG-TERM DRILLING WORKFORCE              | people                 | Constant        | Workforce              |
| Miner Productivity                        | (barrels/person)/year | Stock           | Productivity           |
| Mining                                    | barrels/year           | Flow            | Oil Extraction         |
| Mining Oil Reserves                       | barrels/year           | Stock           | Oil Extraction         |
| Mining Workforce                          | people                 | Stock           | Workforce              |
| Net land use                              | km2/year               | Flow            | Environmental Well-Being |
## Table 1: Model Parameters

| 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 SHIPPING              | million barrels/day | Constant | Oil Extraction         |
| Total workforce             | people      | Auxiliary             | Workforce              |
| Wages                       | dollars/year| Auxiliary             | Economic Well-Being    |
| Water Available             | barrels/year| 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/year| 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|

### Authors' contributions
All authors have contributed equally to the literature review, model development, data collection, analysis, and writing. There is no potential conflict of interest.

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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/ivanw-taylor/Oil-Sands](https://github.com/ivanw-taylor/Oil-Sands).

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