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Predicting Project Environmental Performance under Market Uncertainties: Case Study of Oil Sands Coke

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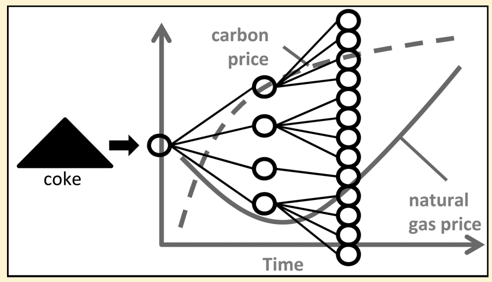
Supporting Information

ABSTRACT: A method combining life cycle assessment (LCA) and real options analyses is developed to predict project environmental and financial performance over time, under market uncertainties and decision-making flexibility. The method is applied to examine alternative uses for oil sands coke, a carbonaceous byproduct of processing the unconventional petroleum found in northern Alberta, Canada. Under uncertainties in natural gas price and the imposition of a carbon price, our method identifies that selling the coke to China for electricity generation by integrated gasification combined cycle is likely to be financially preferred initially, but eventually hydrogen production in Alberta is likely to be preferred. Compared to the results of a previous study that used life cycle costing to identify the financially preferred alternative, the inclusion of real options analysis adds value as it accounts for flexibility in decision-making (e.g., to delay investment), increasing the project's expected net present value by 25% and decreasing the expected life cycle greenhouse gas emissions by 11%. Different formulations of the carbon pricing policy or changes to the natural gas price forecast alter these findings. The combined LCA/real options method provides researchers and decision-makers with more comprehensive information than can be provided by either technique alone.



■ INTRODUCTION

Life cycle assessment (LCA)[1,2] is a valuable tool for assessing environmental impacts of projects as it considers not only the operating impacts of the project itself, but the impacts associated with the project inputs, as well. Traditionally, however, it does not include operational flexibilities (e.g., the option to change operating conditions in the future) or uncertainties, which can result from commodity prices, the application of technologies, or project execution. Real options analysis[3,4] is able to capture the impacts of flexibility and uncertainty on decision-making but has traditionally focused on financial analyses of projects. The method developed in this paper is a unique combination of LCA and real options analyses to account for operational flexibility and to predict a project's life cycle environmental and financial performance over time, under uncertainties in key project financial and environmental drivers. The results of our analysis provide industry with more comprehensive information on which to base their decisions, and government, for example, with better insights into industry choices so that they may plan policies accordingly.

Real options analysis quantitatively values flexibility in decision-making under uncertainty, and incorporates that value into traditional net present value (NPV) analyses. For example, decision-makers often have the option of waiting and investing in a project after some of the uncertainty has been resolved, rather than having to make a final decision at the design phase of their project. A real options analysis quantifies the financial gain (or loss) over the planning horizon of exercising that flexibility. Using such data, the analysis can generate decision sequences that are optimized in terms of the decision-maker's objective function (e.g., maximize a project's NPV). These sequences can be illustrated in the format of a decision-tree. Further details can be found in refs 3 and 4.

Various approaches have been taken by previous studies to account for uncertainty in LCA, including Monte Carlo analyses (e.g., ref 5). There have also been earlier combinations of LCA and real options analyses. Zhang et al.[6] combined LCA with dynamic programming to identify the optimal time to make certain investments with the objective of minimizing life cycle greenhouse gas (GHG) emissions, energy use, or costs. However, their real options component did not allow for

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stochastic variations in key drivers of the project's financial and/or environmental performance, instead using an autoregression model based on an approximated stochastic process.

This paper builds on this previous work by developing a method combining life cycle and real options analyses (combined LCA/real options method) in which key parameters vary stochastically over time. This method is then applied to the case of using oil sands byproduct coke, to investigate how decisions on this issue are impacted by uncertainty in natural gas and carbon prices, and the implications for overall financial and environmental performance.

The oil sands are a large, unconventional petroleum resource located primarily in Alberta, Canada. The petroleum, called "bitumen", is a heavy, highly viscous form of oil that often undergoes processing (or "upgrading") to produce a lighter, sweeter crude before being sent to refineries. One method of upgrading is delayed coking, which produces a solid, high-carbon, high-sulfur byproduct called "coke". Our prior analysis[7] investigated potential uses for coke, through the development and application of a Decision-Support Framework, including LCA, life cycle costing (LCC; a method for evaluating the financial performance of a project over its entire life cycle) and sensitivity analysis. The sensitivity analysis revealed natural gas and carbon prices to be two of the most important variables in the analysis. However, the probabilities of changes occurring in these values were not considered quantitatively, nor was consideration given to how the prices may evolve over time. The flexibility of decisions on coke use was also not considered quantitatively; for example, if natural gas price changes partway through the planning horizon, does the decision-maker have a contingency plan that allows them to minimize negative impacts? This study addresses these limitations and identifies the expected financial and environmental implications of coke use over the planning horizon.

■ METHOD

The combined LCA/real options method consists of four steps as described below. While real options analysis could deal with purely environmental factors rather than financial (e.g., the objective might be to minimize GHG emissions), this paper will focus on financial objectives which internalize the environmental impacts of GHG emissions by considering a financial cost for them.

Step 1. Initial Assessment of Method Suitability. The combined LCA/real options method is beneficial when the following conditions are met: (1) The project has some physical component (and is not purely a financial transaction) and therefore necessarily has environmental impacts; (2) The project has a relatively long life (a simpler method may be more appropriate for examining the environmental impacts of a short-term project); (3) The financial implications of the project are significant, therefore benefitting from detailed analyses, and may result in trade-offs when the environmental implications are also considered; (4) The decision-maker has flexibility, for example to change the way the project is operated at some point in the future (i.e., different courses of action, or alternatives, to pursue); and, (5) Decisions are made under uncertainty large enough that they may change depending on how the uncertain parameters evolve [e.g., future commodity prices; this criterion is revisited after completion of the LCC (Step 2)].

Step 2. LCA and LCC Analyses. If the above criteria are met, LCA and LCC analyses are employed to gain an understanding of the static environmental and financial performance of each alternative under consideration. A detailed discussion of these methods can be found in ref 7. The behavior of the LCC results under uncertainty is investigated in Step 3 and will inform the decision of whether or not to undertake the combined LCA/real options method. Further, data and results from the LCA and LCC analyses will be used in the real options analysis and identification of environmental impacts.

Step 3. Final Assessment of Method Suitability. The fifth criterion from Step 1 is revisited here to determine whether variations in the key drivers of the LCC results will change which alternatives are preferred. Sensitivity analysis is used to both identify those key drivers and investigate their impacts on the results. For example, if a commodity price is the only key driver for an analysis and a change in that price does not change the relative rankings of the alternatives under consideration, the combined LCA/real options method is not required to gain insights into environmental impacts over time: they will be those of the preferred alternative, regardless of how the financial performance varies.

Step 4. Real Options Analysis and Examination of Environmental Implications. If the combined LCA/real options method is found to be appropriate, then the analyst undertakes a real options analysis[3] in which key drivers of the LCC analysis are the modeled uncertainties. There are multiple methods for undertaking real options analyses, for example, dynamic programming,[4] stochastic dynamic programming,[8] stochastic programming,[9] contingent claims analysis,[3] Black and Scholes formulation.[4] We employ stochastic dynamic programming. Dynamic programming was considered but deemed inferior for this application; the dynamic programming method is discussed in Supporting Information (SI).

For each decision (e.g., selection of a particular alternative to maximize financial value) identified by the stochastic dynamic programming, a corresponding environmental impact can be identified from the LCA results. The LCA results are normalized to a functional unit, typically based on a project's primary input or output (e.g., tonne of coke, t coke). If the LCA results are constant over time, as for steady-state operations, then for each decision identified by the real options analysis, the environmental impact is the product of the selected alternative's LCA result and the project's total primary input or output over the relevant time step (e.g., t coke per year). This environmental product is then multiplied by the probability of the decision occurring. If the LCA results vary over time, then the timing of the decision must also be considered when selecting the LCA results to employ in the analysis.

Coke Case Study. The case study examines the overall project of "oil sands coke use". Each decision made will be a selection from among nine alternatives or "pathways". Life cycle inventory (LCI) and LCC analyses were completed in a previous study[7] for seven of these pathways: stockpiling; gasification to produce hydrogen (H_2) either for use by the oil sands extraction and upgrading project (H2/On-site), or by industry at Edmonton, Alberta (the potential large market for H_2 nearest to the oil sands; H2/Edmonton), each without and with the inclusion of carbon capture and storage (CCS) technology (H2/On-site + CCS, H2/Edmonton + CCS); and, sale of the coke to China for electricity generation by integrated gasification combined cycle (IGCC), without and with CCS (Elec/China IGCC, Elec/China IGCC + CCS). The six H2 and Elec pathways were identified as the "most promising" from among a larger set of pathways based on their financial performance, from the perspective of the decision-maker: the Upgrader.[7] Although, it should be noted that neither gasification nor CCS are widely used and so the uncertainties associated with their performances are relatively high; the implications of these and other uncertainties are considered in the Results and Discussion. Stockpiling was retained among the most promising pathways as the baseline, and still a viable alternative.[7] Each pathway describes the life cycle activities associated with a coke-use alternative from the point where the coke is available for use (i.e., excluding its production) to the production of the end-product (H_2 or electricity) or coke stockpiling.[7] Each pathway (except stockpiling) also has an associated conventional fossil fuel "reference" pathway (coal-fuelled IGCC for the Elec pathways, and H_2 production from natural gas for the H2 pathways).[7] The financial performance of each coke pathway is reported relative to the performance of its reference fuel pathway. This method "...account[s] for the need of the coke pathways to be cost-competitive with the reference pathways",[7] and avoids the need to consider additional, variable commodity prices (i.e., hydrogen, electricity). For H2/On-site the "revenue" of the coke system is the avoided cost of the natural gas system which would be used in the absence of coke (here the system is operated on-site by the Upgrader).[7] For the H2/Edmonton and Elec pathways (in which coke is sold to a third-party), the selling price of coke is calculated such that the cost of producing either H_2 or electricity is the same whether a coke or conventional fuel pathway is pursued.[7] The Elec pathways were investigated at three distinct coal prices (low, medium, high).[7] The LCI determined the GHG and selected criteria air pollutant implications of each coke pathway in both absolute (coke pathway only) and incremental (coke pathway relative to reference pathway) terms. Our previous work[7] investigated internalizing the cost of GHG emissions through a carbon tax. This analysis considers both a carbon tax and a cap and trade regime, as discussed below.

The current analysis considers two pathways in addition to those considered previously: H2/On-site (retrofit) and H2/On-site (retrofit) + CCS. The Upgrader has the option of investing in an on-site H_2 production system (H2/On-site) at some point after time zero. However, since the H_2 is a necessary input to the upgrading process (in which coke is produced), delaying investment would require that a conventional natural gas-fuelled system [a steam methane reformer (SMR)] be built and operated until that coke system investment is made. As a consequence, the revenue to the Upgrader from the H2/On-site pathway can no longer include the avoided capital cost of the SMR. The H2/On-site (retrofit) pathways are identical to the H2/On-site, except they account for this reduced revenue.

The real options analysis treats natural gas and carbon prices as stochastic variables and takes a stochastic dynamic programming approach to identify decision sequences that are optimized in terms of the objective function: maximize the expected value of the project net present value [E(NPV)]. Carbon prices are investigated under cap and trade and carbon tax regimes since both are widely debated in North America as potential means of mitigating GHG emissions and carbon prices are expected to vary differently under each with arguably different degrees of uncertainty. Under the cap and trade regime, emitters are allotted a certain number of emissions credits. It is assumed in this analysis that these credits may be traded in an open market, and as such, the price of carbon (i.e., the average financial value of a carbon credit) will vary stochastically over time. Under a carbon tax regime, a charge is added to the price of a carbon-containing material based on the GHG emissions that will result from its use (e.g., combustion). The carbon price is that additional charge per unit of carbon dioxide-equivalent (CO_2E) emitted. In this analysis, it is assumed the price will remain constant over time, unless the regulator chooses to increase it at a predefined future time. In this analysis, both the cap and trade and carbon tax policies are assumed to apply to all GHG emissions (e.g., not just combustion emissions) and to apply internationally. Primary assumptions for the real options analysis are described in Table S2 (in Supporting Information) and in the following text sections. The model is developed in Visual Basic using Microsoft Excel as a user-interface.

Natural Gas. Natural gas price is modeled as a mean-reverting process with the mean including an increasing trend. This is the Ornstein–Uhlenbeck process (described in, e.g., refs 3 and 10); the discrete version used is shown in eq 1. Commodity prices have been found to be well-described by mean-reverting models.[10] The increasing trend makes the price process stationary, so that it is reverting to its trending mean. This captures well the predicted price behavior (see below and Figure S1 in Supporting Information).

$$y_t - y_{t-1} = \kappa(y_{m,t} - y_t) \tag{1}$$

where y_t is the natural logarithm of price at time t, κ is the mean-reversion factor, and $y_{m,t}$ is the mean price at time t. We employ the discrete time and state scenario tree of Hahn and Dyer[10] to represent this uncertainty and append it to include an increasing trend in the mean. In the base case, $y_{m,t}$ increases linearly over time, based on regression of price data from 1975 to 2035.[11,12] However, the slope and intercept, as well as the mean-reversion factor (based on regression of eq 1 over the same time period, assuming κ greater than or equal to zero) and volatility [standard deviation of $(y_t - y_{t-1})/y_{t-1}$ for historical data, 1975–2009] are user-input variables that can be adjusted to examine alternative scenarios. In the base case, the resulting natural gas price tree covers a range from \$0.69/GJ to \$36/GJ at the end of the 16-year planning horizon, with an expected value of \$5.3/GJ (see Figure S2 in Supporting Information). However, there is additional uncertainty in projections of future natural gas prices. The projection used here, from the U.S. EIA,[12] "generally" increases over time but is described as highly uncertain, "...particularly in light of the growing development of shale gas resources". In the U.S. EIA[12] forecast, shale gas meets 24% of U.S. demand by 2035; if the shale gas industry should falter (based on environmental concerns, for example), meeting this demand from other sources could result in significantly higher prices. As such, markedly faster price growth (to an expected value of \$14/GJ at the end of the horizon) is investigated in the sensitivity analysis. The base case parameter values are shown in Table S2 (Supporting Information).

Cap and Trade. Carbon price under a cap and trade policy is modeled as a jump of known size occurring at an unknown time (Bernoulli process), followed by geometric Brownian motion[3] (GBM), see eqs S1 and S2 in Supporting Information. The Bernoulli process represents the regulatory action of implementing a cap and trade policy, while the GBM is commonly used to model permit price evolution (e.g., refs 15 and 16 both used GBM to model carbon prices, although both also included the potential for a jump during the horizon due to policy changes, etc.). The discrete time and state scenario tree for the GBM is generated using a binomial tree as described in Luenberger.[17] As with natural gas, the natural logarithm of the price is modeled. The initial jump in price (i.e., implementation of the policy) is set at \$20/t CO_2E; a review of relevant data[13] and literature[14,15,18,19] suggested a jump in the range of \$10 to \$30/t CO_2E. The probabilities assigned to the jump occurring are highly uncertain and a different scheme is investigated in the sensitivity analysis. In the base case, for years one through five, the probabilities are based on those identified by Point Carbon[14] for the U.S. for the years 2010 to 2014. Volatility is calculated as the standard deviation of the natural logarithm of European Union (EU) Emissions Trading Scheme (ETS) historical prices[13] (2005−2010; only partial data available for 2005 and 2010), divided by the mean, yielding a value of 50%. This volatility is high: Future cap and trade schemes may learn from the experiences of the EU ETS and thus have lower volatilities; this potential is investigated in the sensitivity analysis. Finally, drift is equal to the mean annual change in the natural logarithm of expected carbon prices over the first 12 years of data given by Kettunen et al.[20] Future carbon prices and their associated probabilities are predicted using the "bracket-mean" method.[20,21] The cap and trade policy is modeled as both replacing and augmenting Alberta's current carbon pricing policy;[22] the base case assumes augmentation.

Carbon Tax. Carbon price under a carbon tax is modeled as a jump of known size, at an unknown time, followed by a period of constant price, after which there may be another jump of known size (with known probability) [Bernoulli processes; see eq S1, Supporting Information]. This process mimics the regulatory environment under which a carbon tax is instituted; the possible second jump describes regulatory uncertainty, that is, as time passes, regulators may choose to adjust the level of the tax. There is precedence for this as some existing carbon taxes have been modified over time.[23] The size and probability of the initial jump are the same as for the cap and trade policy for consistency in the analysis; however the initial jump size is consistent with those of implemented policies.[24,25] The remaining parameter values identified in Table S2 (Supporting Information) are chosen as reasonable first approximations and investigated in a sensitivity analysis. The carbon tax is also modeled as replacing or augmenting Alberta's current carbon pricing policy;[22] the base case assumes augmentation.

Decision-making Scheme. The objective function underlying the decisions, along with other primary variables, is shown in Table S2 (Supporting Information). It is assumed that coke sales (relevant for the H2/Edmonton and Elec/China IGCC pathways) are made under two-year off-take agreements, under which 2.5 million t of coke [per ref 7; 74 million GJ (ref 26)] are sold each year. As such, the analysis progresses in two-year increments. A decision-tree of natural gas and carbon prices is developed, showing all possible values for these prices at each time step, and their associated probabilities. The Upgrader may switch among any of the H2/Edmonton and Elec/China IGCC pathways at any time step. However, once the Upgrader has invested in an on-site pathway, it is assumed it must continue to operate that pathway for the remainder of the planning horizon; investment in H2/On-site (without or with CCS) may only be made at year zero. Further, no construction lag is included in this analysis; operations begin as soon as the decision is made to pursue a pathway.

Stochastic Dynamic Programming. At each time step, the value of each coke pathway at each node of the decision tree is determined in constant 2008\$ using the data (e.g., nonfuel operating costs, capital costs) from the LCC and LCA analyses and the natural gas and carbon prices specific to that node. The recursion proceeds according to eq 2:

$$
\begin{cases}
C(\Delta_{0,1}) = \max_{\alpha\in\{0,1,4\ldots n\}}\left\{\begin{array}{l}\mathrm{PV}(\Delta_{0,1})_{\alpha\in\{4\ldots n\}} + \displaystyle\sum_{z\in r(0,1,\mathrm{dt})} P(\Delta_{\mathrm{dt},z})C(\Delta_{\mathrm{dt},z}),\\ \mathrm{PV}(\Delta_{0,1})_{\alpha\in\{0,1\}} + \displaystyle\sum_{x=dt}^{T}\sum_{z\in r(0,1,x)} q(\Delta_{x,z})\mathrm{PV}(\Delta_{x,z})_{\alpha\in\{0,1\}}\end{array}\right\}\\
C(\Delta_{t,i}) = \max_{\alpha\in\{2\ldots n\}}\left\{\begin{array}{l}\mathrm{PV}(\Delta_{t,i})_{\alpha\in\{4\ldots n\}} + \displaystyle\sum_{z\in r(t,i,t+\mathrm{dt})} P(\Delta_{t+\mathrm{dt},z})C(\Delta_{t+\mathrm{dt},z}),\\ \mathrm{PV}(\Delta_{t,i})_{\alpha\in\{2,3\}} + \displaystyle\sum_{x=t+\mathrm{dt}}^{T}\sum_{z\in r(t,i,x)} \frac{q(\Delta_{x,z})\mathrm{PV}(\Delta_{x,z})_{\alpha\in\{2,3\}}}{q(\Delta_{t,i})}\end{array}\right\} t = \mathrm{dt}\ldots T-\mathrm{dt}\\
C(\Delta_{T,i}) = \max_{\alpha\in\{2\ldots n\}}\{\mathrm{PV}(\Delta_{T,i})_{\alpha}\}
\end{cases}
\quad (2)
$$

Where (see Figure S3 for further information on how the variables relate to the decision tree structure, Supporting Information) $C(\Delta_{t,i})$ = value of the decision made [i.e., pathway selection] at node $\Delta_{t,i}$, $\Delta_{t,i}$ = node, i at time, t, t = time, 0 to T, α = coke pathway index, 0 to n, n = number of coke pathways [9; 0 − 3 are the Upgrader investment pathways H2/On-site, H2/On-site + CCS, H2/On-site (retrofit), and H2/On-site (retrofit) + CCS, respectively; 4−9 are the remaining H2 and Elec pathways which may be pursued under two-year off-take agreements], $\mathrm{PV}(\Delta_{t,i})_\alpha$ = present value of pathway α at node $\Delta_{t,i}$ [constant 2008\$], $r(t,i,j)$ = index of child nodes at time, j, of node $\Delta_{t,i}$, 1…$s(t,j)$, $s(t,j)$ = number of child nodes at time, j, of a node at time, t [e.g., under uncertainties in natural gas price and cap and trade implementation, $s(t,j) = m(j-t)$, $P(\Delta_{t,z})$ = probability of node $\Delta_{t,z}$ occurring, relative to its parent node, dt = step size, constant [2], T = horizon [14 in this case, since the analysis begins at year 0], $q(\Delta_{t,z})$ = probability of node $\Delta_{t,z}$ occurring, relative to time zero; the product of all $P(\Delta)$ along the tree path from time, zero to node, z at time, t, i = node index, 1 to $m(t)$, and $m(t)$ = number of nodes at time, t [e.g., under uncertainties in natural gas price and cap and trade

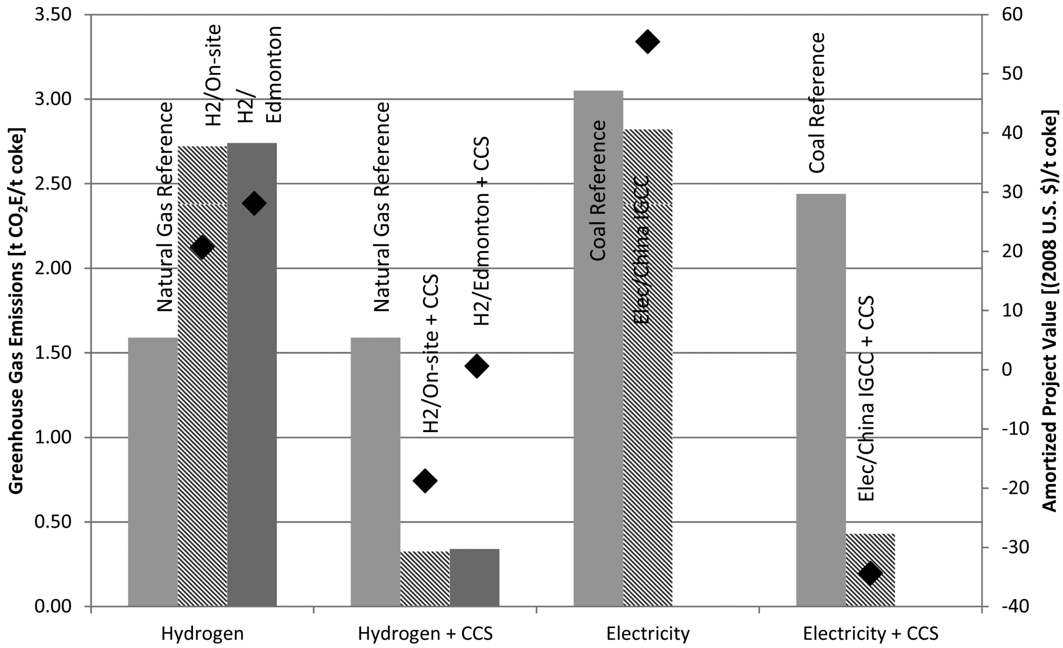

Figure 1. Life cycle greenhouse gas emissions of coke and conventional fuel reference pathways, and amortized project values of coke pathways, from ref 7. Notes: Amortized project value: "annual worth divided by annual coke consumption";[7] note this is based on a 15 y horizon,[7] whereas the analysis completed in this paper uses a 16 y horizon; Elec/China IGCC (+CCS) values are based on the low coal price, and all values include Alberta's current carbon pricing policy.[22] Carbon capture and storage (CCS) is applied only to the coke pathways; differences in reference pathway performance between the without and with CCS scenarios are due to the coke and reference pathways being designed to produce the same output and the efficiency of the coke pathways decreasing in the CCS scenarios; in the case of Elec/China IGCC there is a 20% (relative) efficiency penalty associated with adding CCS, while for the H2 pathways this penalty is only 3%;[7] this results in a significantly larger change in performance for the coal reference pathways than for the natural gas reference pathways on a per tonne coke basis. Coal reference: Electricity generation at Shanghai by coal-fired integrated gasification combined cycle (IGCC); Elec/China IGCC, Elec/China IGCC + CCS: Electricity generation at Shanghai by IGCC, without and with CCS; H2/Edmonton, H2/Edmonton + CCS: Hydrogen (H_2) production at Edmonton for sale to market, without and with CCS; H2/On-site, H2/On-site + CCS: H_2 production on-site for use by the oil sands upgrader, without and with CCS; Natural gas reference: H_2 production from natural gas through steam methane reforming (SMR). The newly added H2/On-site (retrofit) and H2/On-site (retrofit) + CCS pathways have the same life cycle greenhouse gas emissions performance as the H2/On-site pathways.

implementation, $m(t) = \{1 \text{ when } t = 0;\ 4^{t/\mathrm{dt}} \text{ when } t > 0\}$; see Figure S3, Supporting Information].

The stochastic dynamic programming maintains the path-dependency throughout the tree by considering each node only in terms of its own value [$\mathrm{PV}(\Delta_{t,i})$] and the values of its child nodes [$z \in r(t,i,t + \mathrm{dt})$]; in the case of investments in H2/On-site and H2/On-site (retrofit) (without or with CCS) this means considering the entire subtree of child nodes [all $z \in r(t,i,x)$, from $x = t + \mathrm{dt}$ to T]. The ratio of $q(\Delta_{x,z})/q(\Delta_{t,i})$ describes the probability of node $\Delta_{x,z}$ relative to node $\Delta_{t,i}$; required to properly determine the value of an investment made at time t. The expected value of the entire decision tree [E(NPV)] is equal to $C(\Delta_{0,1})$. As evident from eq 2, the analysis begins at the horizon (T; in this case the year 14 time step) and proceeds "backward" to time zero, with the last decision based on data for years zero and one (because of the two-year time step; see Supporting Information).

Based on the objective function, the optimal decision (pathway selected) at each node is that which maximizes the financial value, regardless of how much higher that value is than what would be achieved by another pathway. In reality, these decisions may also be influenced by other factors (e.g., a reluctance to move from the status quo), so that some "value difference threshold" would have to be reached before a switch between pathways was made (e.g., continue selling to Elec/China IGCC unless the value of another pathway is at least 10% higher).

The stochastic dynamic programming identifies the probability that each pathway will be financially preferred at each time step. As a consequence, expected environmental impacts of coke use at time t are determined by identifying each pathway's (α_t) two-year environmental impacts (from the LCA results) at that time (t), multiplying by the probability of that pathway being preferred at time t, and then summing over all pathways.

CASE STUDY RESULTS AND DISCUSSION

Step 1. Initial Assessment of Method Suitability. The case of oil sands coke use meets the initial set of criteria for the combined LCA/real options method: (1) It is a "physical" project and there are environmental consequences associated with the potential coke pathways; (2) The pathways involve the operation of facilities that are expected to last approximately 30 years; (3) The H2 and Elec pathways all involve significant capital investments (in the \$1.5 to \$2 billion range), as well as have operating costs and revenues over the planning horizon, making them good candidates for LCC analyses as well as potentially resulting in trade-offs when the GHG emissions are also considered; (4) The Upgrader may switch between pathways as often as it chooses over the planning horizon, unless it has invested in an on-site pathway, but this decision is itself flexible in terms of timing; and (5) The choice among coke pathways is influenced by variations in natural gas and

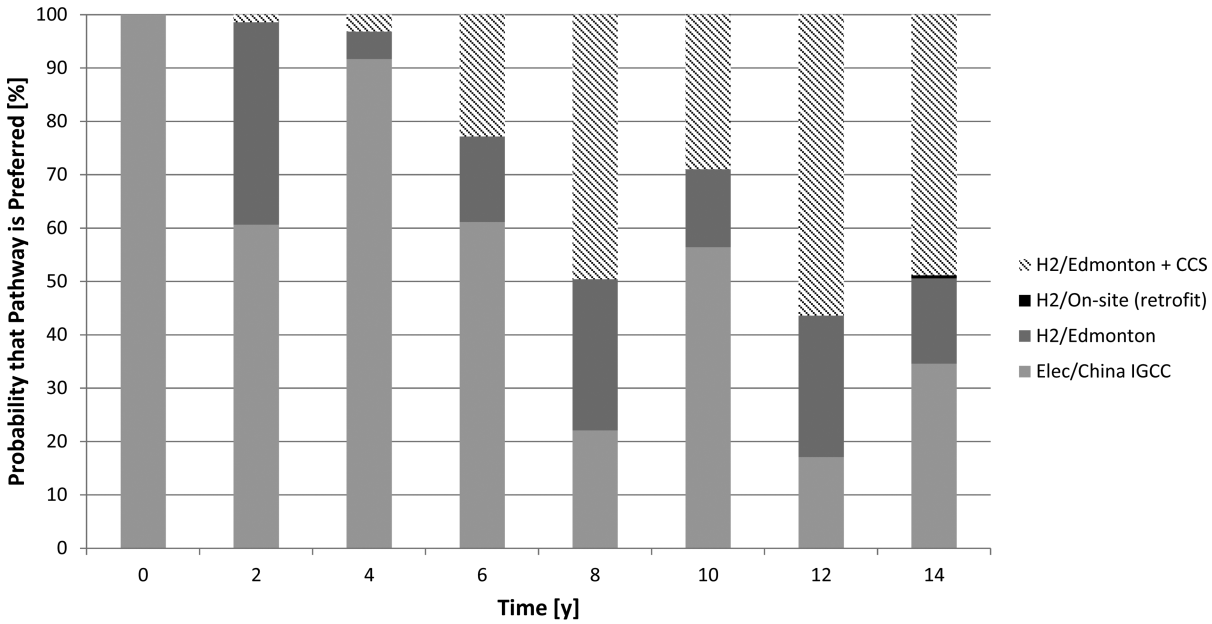

Figure 2. Financial preference for each coke use pathway over time under base case uncertainties in natural gas price and carbon tax implementation. Notes: Pathways that are never preferred are not plotted, these include: Stockpiling, Elec/China IGCC + CCS, H2/On-site (retrofit) + CCS, H2/On-site, and H2/On-site + CCS. Pathway definitions per Figure 1, except: H2/On-site (retrofit), H2/On-site (retrofit) + CCS: Same as H2/On-site (+ CCS), but built after upgrader start-up and operation with steam methane reformer; Stockpiling: Stockpiling of coke on-site by the Upgrader. Except for stockpiling, all pathway financial performances are based on the performances of their conventional fuel reference pathways (natural gas for the hydrogen pathways, coal for the electricity generation pathways).

carbon prices[7] which are uncertain over time, but of a scale that may reasonably be expected to occur over the planning horizon.

Step 2. LCA and LCC Analyses. The LCA and LCC analyses results for the seven pre-existing coke pathways are taken from our previous study;[7] the life cycle GHG emissions of the H2 and Elec pathways and their conventional fossil fuel reference pathways are shown in Figure 1. The additional pathways added in this analysis [H2/On-site (retrofit), H2/On-site (retrofit) + CCS] have environmental performances identical to those of the H2/On-site pathways, while their financial performances are considerably worse [by about $600 and $580 million (NPV) in the without and with CCS pathways, respectively]. Therefore, the most financially attractive pathway is still Elec/China IGCC.

Step 3. Final Assessment of Method Suitability. The sensitivity analysis conducted in our previous work[7] revealed that under certain natural gas prices and carbon taxes, the financially preferred pathway (Elec/China IGCC) could switch to H2/Edmonton or H2/On-site (recall that the financial performance of each coke pathway is based on the performance of its reference fuel pathway). While coal price (used in the Elec reference pathways) is also an important driver of the LCC results, switching between the three investigated prices (low, medium, high) does not change the financial dominance of Elec/China IGCC, when all other parameters are held at their base case values.[7] The coal price is assumed to be constant in the real options model, but uncertainty is investigated parametrically by examining the three different prices in the sensitivity analysis; the low coal price is assumed in the following base case analyses.

Step 4. Real Options Analysis and Environmental Implications. The real options analysis indicates that uncertainty in natural gas and carbon prices significantly impacts the projected financial performance of the coke use pathways, and hence overall decision-making and projected environmental performance. Based on our previous LCC analysis results,[7] with a natural gas price of $5.0/GJ and no carbon tax, Elec/China IGCC was financially preferred, even at the low coal price. However, based on the results of the real options analysis, with the expected natural gas price increasing over time and the expectation of a carbon tax being implemented at some point during the planning horizon, Elec/China IGCC is financially preferred only at the beginning of the horizon, ultimately being replaced by an H2 pathway.

The stochastic dynamic programming indicates that Elec/China IGCC is likely to be replaced by H2/Edmonton + CCS, after about eight years (Figure 2; see Supporting Information for further insights into the decision-making process). At year eight, the probability of Elec/China IGCC having the best financial performance is only 22%, compared to 50% for H2/Edmonton + CCS. For Elec/China IGCC, that is a decrease of 78% (absolute) from year zero to year eight. The overall E(NPV) of the decision tree is $1.1 billion, an increase of 25% compared to pursuing Elec/China IGCC over the entire horizon, under the same natural gas and carbon tax uncertainties (see Table S3 for comparisons to other pathways, Supporting Information). Therefore, the Upgrader's flexibility in its decisions on coke use is valuable: By being able to switch pathways partway through the horizon, and not commit to a single pathway at time zero, it has the potential to significantly increase its overall financial performance (depending on how prices actually evolve over time).

Notably, the real options analysis does not identify H2/On-site as a likely pathway under the base case carbon tax implementation. The LCC sensitivity analysis identified the H2/On-site pathway as preferred at carbon prices between $23 and $200/t CO_2E.[7] Since the coke is never sold in H2/On-site it is never subject to the tax; its natural gas reference pathway is however, resulting in strong positive financial performance for H2/On-site under a carbon tax. In the real options analysis, although the carbon tax is implemented at \$20/t CO_2E, the uncertainty means the expected value of the price only reaches \$17/t CO_2E by the end of the planning horizon. Implementing the tax at \$30/t CO_2E (so its expected value reaches \$24/t by the end of the horizon) increases the probability of H2/On-site (retrofit) being preferred (to 16% at year 14).

Figure 2 shows a clear trend in the preference for Elec/China IGCC: In addition to declining over time, it alternately increases and decreases at each time step. This alternating behavior is a consequence of the mean-reversion in the natural gas prices, the impact of natural gas price on the pathway preference, and the overall structure of the tree. For example, at years two and six, the highest probability nodes in the decision tree have natural gas prices of either \$3.8/GJ or \$6.6/GJ and so the financial preferences are split between the Elec and H2 pathways. At year four, the nodes with the highest probabilities have natural gas prices of \$5.0/GJ or less, resulting in an increased preference for Elec/China IGCC. A natural gas price above \$5.0/GJ appears to result in an H2 pathway being preferred in these time steps (consistent with the sensitivity analysis results of the LCC,[7] wherein a price above \$6.0/GJ shifted the financial preference from Elec/China IGCC to H2/Edmonton).

The combined LCA/real options method also reveals potential changes to the expected environmental impacts of the coke use project, compared to what would be expected based on the LCC and LCA results, alone. Based on the results in Figure 2, cumulative incremental GHG emissions (i.e., total expected emissions over the planning horizon from the coke pathways relative to total emissions from the conventional fuel reference pathways they are replacing) are expected to be −9.7 million t CO_2E by the end of the horizon; this is a decrease of 11% compared with pursuing Elec/China IGCC over the entire horizon (see Table S3 for comparisons to other pathways, Supporting Information). While Elec/China IGCC has slightly negative incremental GHG emissions (see Figure 1; and so over time cumulative incremental emissions become more negative), the decision tree shows probabilities of implementing H2/Edmonton + CCS at each time step after year zero ranging from 1.5% to 56%; therefore, even though the probability of implementing H2/Edmonton (with its relatively large incremental emissions) ranges from 5.1% to 38% over the planning horizon (years two to 14), the overall emissions decline. However, depending on how natural gas and carbon prices evolve over time, any one of a number of specific decision sequences may be pursued. Based on the LCA results for the four pathways included in Figure 2, emissions will be somewhere between −49 million (H2/Edmonton + CCS over entire horizon) and 45 million t CO_2E (H2/Edmonton over entire horizon).

Figure 2 is based on the implications of natural gas price and carbon tax implementation uncertainties, however cap and trade policies are also commonly suggested as a means of mitigating GHG emissions. Under the base case conditions (Table S2, Supporting Information), implementing a cap and trade system would have different implications for pathway preferences than implementing a carbon tax. Notably, the probability of H2/Edmonton + CCS being implemented declines (see Figure S7, Supporting Information) due to the potential for lower carbon prices under the cap and trade system: Once the carbon tax is implemented, the carbon price is steady at \$20/t CO_2E (until the time when a tax increase may be made), but once the cap and trade policy is implemented at an initial price of \$20/t CO_2E, the price may increase or decrease over time based on geometric Brownian motion. At time steps two through six, for example, H2/Edmonton is preferred over H2/Edmonton + CCS at nodes with carbon prices less than \$20/t CO_2E. Under the cap and trade policy, the expected cumulative incremental GHG emissions over the entire horizon are −1.3 million t CO_2E, an increase of 86% compared to when the carbon tax is implemented. Thus, from the perspective of the policy-maker, the carbon tax seems to be a more effective method of reducing GHG emissions: When both policies are implemented at \$20/t CO_2E, the carbon tax is expected to achieve much greater reductions in emissions. Although, as with the carbon tax, the emissions under the cap and trade policy will depend on how the natural gas and carbon prices actually evolve over time: Based on the LCA results for the four pathways included in Figure S7, emissions will be somewhere between −79 million (Elec/China IGCC + CCS over entire horizon) and 45 million t CO_2E (H2/Edmonton over entire horizon).

While the combined LCA/real options analysis undertaken here addresses uncertainties in natural gas price and carbon price implementation, uncertainties remain in the analysis. For example, the price level at which a carbon tax or cap and trade policy will be implemented may well be different from the \$20/t CO_2E assumed in the base case; as stated above, if a carbon tax is instead implemented at \$30/t CO_2E the pathway preferences change, increasing the expected cumulative incremental GHG emissions by 9.6% over the planning horizon [primarily due to the increased preference for H2/On-site (retrofit)]. Similarly, when the highest probabilities of implementing a carbon tax are shifted nearer the end of the planning horizon, the probability of pursuing H2/Edmonton + CCS does not exceed 5.6% until year eight; the reduced likelihood of using CCS results in cumulative incremental GHG emissions 76% higher than in the base case. If the natural gas drift term is increased from 0.017 to 0.040, the natural gas price increases rapidly over time (to an expected value of \$14/GJ at the end of the horizon) and the likelihood of pursuing Elec/China IGCC is reduced to zero after year four, replaced by increased preferences for H2 pathways. These are all examples that could conceivably occur within the planning horizon, and highlight a limitation of the real options method: The insights yielded by the analysis are still fundamentally dependent on predictions of the future, which are inherently uncertain. They also depend on the performance and cost characteristics of the technologies being studied (operating efficiencies, capital costs, etc.); in this case, these characteristics have relatively high uncertainties as the technologies considered (gasification and CCS) are not widely used. A sensitivity analysis reveals that variations in parameters of this type can have impacts on the same order of magnitude, or much greater, than variations in the real options parameters listed in Table S2, Supporting Information. In addition to the sensitivities discussed above, 15 additional parameters were investigated in the sensitivity analysis, under the base case uncertainties and/or the natural gas price and cap and trade implementation uncertainties (see Supporting Information for detailed results). Variations in the capital cost of gasification, discount rate, coal price and natural gas drift rate all had notable impacts on the overall expected value, for example. It should also be recognized that parameters that have little impact on the overall financial and emissions performances can still have notable impacts on pathway preferences. For example, implementing the carbon tax increase earlier or later in the horizon has little impact on financial or environmental performance, but implementing the change early increases the preference for H2/On-site (retrofit) and introduces a preference for Elec/China IGCC + CCS; conversely, delaying the change removes any likelihood of H2/On-site (retrofit) being preferred, within the uncertainty of the analysis. Thus, the sensitivity analysis has shown that the real options analysis cannot address all uncertainties inherent in the analysis, and care must be taken with not only the determination of the parameters for the real options analysis, but also with the characterization of the inputs originating from the LCA and LCC analyses. A decision-maker would need to consider data beyond these analytical results (e.g., risk tolerances) to make final, informed decisions.

There are both financial and environmental implications of the uncertainty and decision-making flexibility inherent in the case of oil sands coke use; the combined LCA/real options method yields a better characterization of these implications than could be achieved by applying either method alone. Traditional LCA does not incorporate the impact of uncertainty on decision-making, nor flexibility in adjusting decisions as circumstances change. Traditional real options analysis does not consider life cycle environmental impacts, thus restricting its ability to assess the broader implications of e.g., emissions mitigation policies. Thus, real options and LCA complement each other, and when combined, can provide a more holistic view. In the coke case, depending on how the natural gas and carbon prices evolve over time, operating decisions will change and consequently, so will the financial and environmental impacts of coke use. From an industry perspective, the combined LCA/real options method provides insights into which pathways may become most attractive over time, and thus which should be the focus of more detailed engineering studies, market analyses, etc. For example, Elec/China IGCC looks promising in the near term, but eventually hydrogen production becomes more attractive under the base case assumptions. From a policy-making perspective, the data above provide insights into the likely actions of industry over time, and provide policy-makers with the opportunity to develop and implement policy instruments to influence those industry decisions. For example, if the government preferred the coke be used in-province, they may restrict out-of-province sales, or they may implement a carbon tax [e.g., a carbon tax implemented at \$30/t in year two (100% probability) would result in H2/On-site being preferred exclusively over the entire horizon]. The analytical results also indicate that both carbon tax and cap and trade policies offer the potential to achieve negative cumulative incremental GHG emissions over the planning horizon, but a carbon tax seems to be the most effective approach. The base case analysis is, however, still subject to uncertainty, and a change such as implementing a carbon tax at a higher price or using a different natural gas price forecast could alter the financial and environmental results.

Other decisions currently being informed by either LCA and LCC analyses, or real options analysis, would benefit from application of the combined LCA/real options method. The decisions best suited to be informed by the combined method are long-lived, involve significant investment, impact the environment and are based on uncertain data. For example, projects in contexts such as energy system planning and resource-extraction are good candidates for the combined LCA/real options method. The combined LCA/real options method will never provide "perfect" insights; users must be cognizant of the limitations of the method, and use it in conjunction with other tools for informing decision-making. Ultimately however, the combined LCA/real options method is valuable for better characterizing the conditions under which decisions are made, so that decision-makers may be more confident in their choices.

■ ASSOCIATED CONTENT

Supporting Information

Additional details and/or discussion of LCA and LCC analyses; real options analysis; results; and, sensitivity analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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