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Original article

An alternative to carbon taxes to finance renewable energy systems and offset hydrocarbon based greenhouse gas emissions

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ABSTRACT

Carbon taxes are frequently proposed as a means to mitigate the hydrocarbon industry's environmental impact. This paper assesses the potential benefits of an alternative to carbon taxes (ACT), where hydrocarbon producers directly invest a fixed amount per unit produced into renewable energy systems (e.g., wind farms). Producers maintain ownership of the assets and reinvest a portion of revenue from them to further grow the renewable assets. This proposal could help producers gradually evolve from hydrocarbon to renewable energy companies – avoiding the job losses associated with sudden industry shifts. We present an in-depth case study of the Athabasca oil sands, and extend the results to other regions. We find that wind turbines purchased with an ACT of $12/barrel where $0.03/kWh of produced power is reinvested could offset all the greenhouse gas emissions from extracting and refining the region's bitumen, provided wind turbines were located at good wind sites. Finally, to increase the grid's ability to use the wind power generated, energy storage and grid systems should also be an option for ACT investing. Future work should focus on North Dakota, which has extensive hydrocarbon resources collocated with good wind resources.

Introduction

The production and utilization of hydrocarbon resources is increasingly of concern with regard to global warming issues. The production of the Athabasca oil sands, for example, is particularly contentious due to the energy requirements for mining and the nature of the oil extracted; however, it is an integral part of the Albertan economy [1]. The denial of the Keystone XL Pipeline sent a clear signal that the perceived environmental impact of the oil sands is preventing its growth. Accordingly, there has been renewed interest in increasing carbon taxes in Alberta to C$30 (Canadian dollars) per ton of carbon dioxide (CO_2) in 2018 [2]. Traditional carbon tax schemes have two potential issues: first, the revenue collected can be diverted by political action to other perceived important but non-environmental issues, which for example has happened with some U.S. state tobacco taxes [3]; and second, corporations typically oppose perceived business harm induced by downstream tariffs/taxes.

To investigate an alternative to a carbon tax, this paper studies three questions:

1. How much of the GHG emissions of hydrocarbon (e.g. oil) production and use could be offset by a commensurate investment in renewable energy systems (e.g. wind power)?
2. Could such a scheme be achieved if hydrocarbon producers invested a fixed fee per unit (e.g. $/barrel) produced into renewable energy systems, where they maintained ownership of the asset, instead of having a carbon tax where they pay the tax to the government?
3. Does this become more financially viable if hydrocarbon production companies also reinvest a fraction of the revenues from electricity generation from the renewable energy systems into growing the renewables resource?

To answer these questions quantitatively, we present an in-depth case study examining the Athabasca oil sands. The Athabasca oil sands produce bitumen as a raw product through a diverse set of extraction methods. The bitumen is then processed, upgraded, and/or refined by one of several methods. To focus on evaluating these three questions, this paper simplifies the process diversity by using an average value for the GHG emissions of refined oil derived from the oil sands on the basis of a barrel of refined product.

The Athabasca region has been devastated by the drop in oil prices, which have fallen from a 2013 average (in Cushing,

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Nomenclature

\$	U.S. Dollar	GHG	greenhouse gas
ACT	alternative to carbon tax	kWh	kilowatt hour
bbl	barrel	kWh_{wind}	kilowatt hour of electricity generated by wind power
C\$	Canadian Dollar	MT	megatons
CO_2	carbon dioxide	SM	supplemental material
CO_2e	CO_2 equivalent	U.S.	United States

Oklahoma of West Texas Intermediate) of \$98 (U.S. dollars) per barrel (bbl) to a 2015 average of \$50/bbl [4]; \$50 is close to, if not below, the cost of producing and upgrading bitumen from the oil sands [5]. Morgan Stanley estimates crude oil production costs from the oil sands are between \$47–\$84/bbl, which is significantly higher than Middle East oil production which costs between \$10–\$36/bbl [5]. Canada's largest synthetic crude oil producer announced in August 2015 that its break-even production cost for refinery-ready crude oil was \$43.46/bbl and \$47.27 for fully upgraded crude oil [6]. Because of low market prices for crude oil, schemes to offset environmental impact must be creatively funded and cost efficient.

The answers to these three questions are inevitably influenced by the wind speeds in the Athabasca region, which are not high. Lower wind speeds imply that an investment in wind energy as a renewable energy source would be more efficient if sited elsewhere. However, given the massive GHG emissions of the Athabasca oil sands and their large land footprint, we nevertheless set out to understand how much benefit could be gained from wind power in the region. The sensitivity study of this scheme will help to quantitatively assess the viability of similar schemes in higher wind areas.

As a benchmark for any GHG reduction scheme, California's 2015 cap and trade prices for greenhouse gas (GHG) emissions have ranged from \$11–\$13/ton of CO_2 equivalent (CO_2e) [7]. Creyts et al. reported that for less than \$50/ ton of CO_2e, the U.S. could offset between 1300 and 4500 megatons (MT) of CO_2e annually [8]. Therefore, viable mitigation schemes need to be more cost efficient than \$50/ ton of CO_2e.

The framing of the three questions we set out to investigate assumes a model of corporate ownership that has been typical of the U.S.' history of wind power development [9]. Models of corporately owned wind farms neglect the European experience that has shown that community owned wind projects: reduce community resistance to wind projects, access capital at a cheaper rate than debt-based financing of limited-liability corporate entities, and create smaller projects that are distributed more evenly across the grid [9]. However, due to the scale of the Athabasca oil sands and their GHG emissions, an equally large wind project will be required. At this scale, community-owned projects are not typically an option. We however note that before the full-scale project would begin, community-owned and financed wind power projects could help to increase community buy-in and build momentum for the larger project.

Typically large wind projects are financed using a limited liability structure which shifts the project risk onto the lending agency [9]. This financing model increases the cost of capital and slows down the project evaluation phase [9]. The proposed scheme would fund the wind farm with a per-barrel fee – thus enabling a debt-free funding source and allowing the use of limited-liability structures without their typical drawbacks. With oil companies having direct ownership of the asset, they are apt to care more about its success, and will with time learn how to manage the resource as they potentially transform themselves into renewable energy companies.

Public opposition to wind projects is nuanced [10,11]; the most common reason for public resistance to major wind farms is the undesirable visual impact of wind farms [11,12]. As such, we note that one additional benefit to co-locating wind turbines with oil extraction sites is that these sites are typically far from the public eye and are already aesthetically compromised.

In this paper we present a Excel-based Modeling tool to test the hypothesis that allowing oil producers to invest in on-site or if needed remote wind turbines, instead of being subject to a government-collected carbon tax, can help to offset the GHG emissions from the production and end-use of crude oil from the oil sands. The tool also allows for including the condition that producers reinvest a fraction of the revenue from the wind turbines towards the installation of more wind turbines.

Methods

An Excel-based modeling tool

Uncertainty is high with projects such as the one proposed in this paper; we address this uncertainty by clearly stating the values we have used in the model and by providing the Microsoft Excel-based modeling tool in the Supplementary Material (SM) so that readers can adjust model inputs to match their circumstances, location, or perspective on what an appropriate value should be for any one of the many estimations made in this paper (Fig. 1). (For more details on fine-tuning the model, see the SM.)

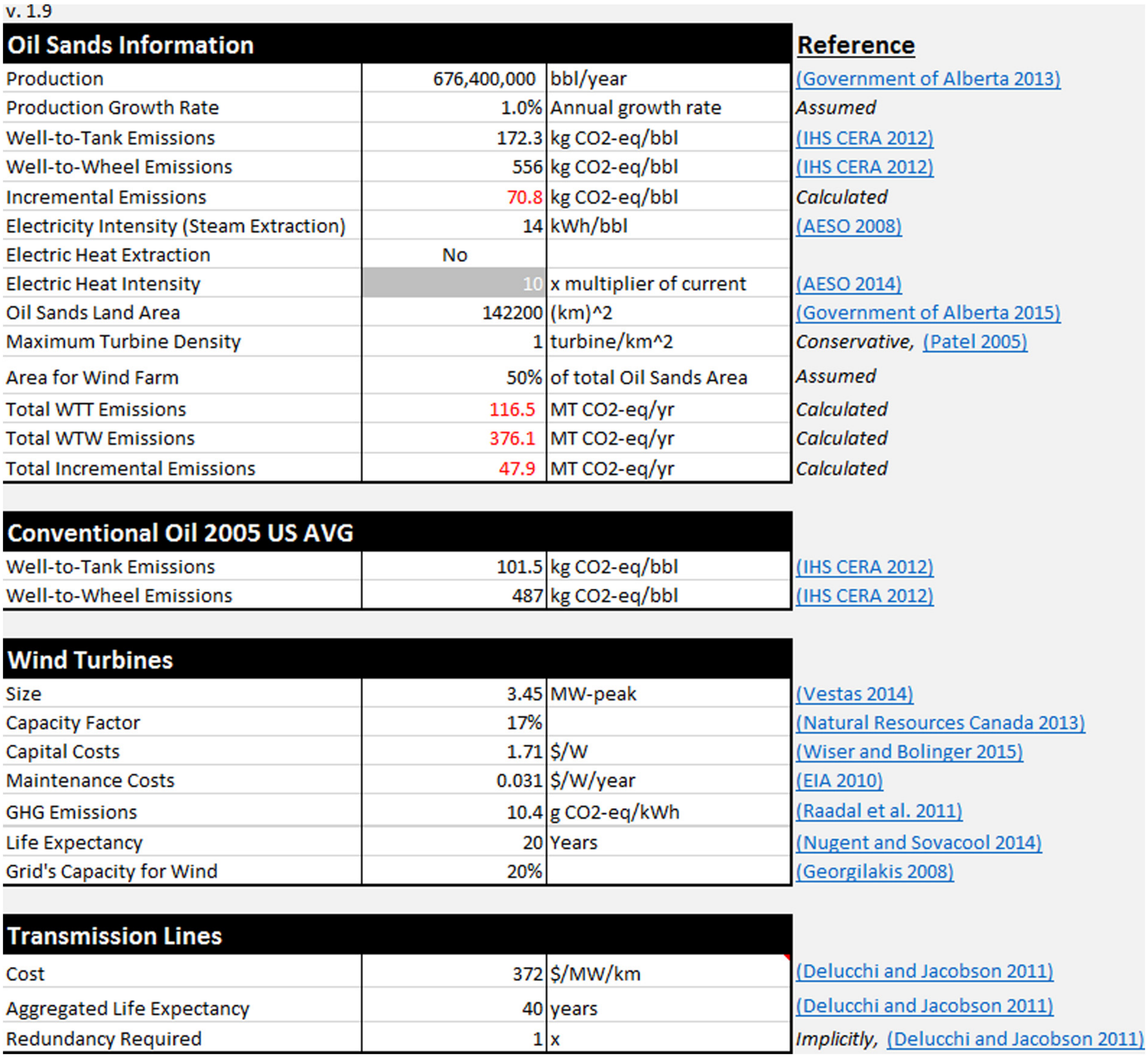
The use of U.S. dollars for currency accounting

Most of the published cost and price estimates for wind turbines and crude oil are reported in U.S. Dollars (\$). Given the volatility of the U.S.–Canada exchange rates from 2000–2015, the model's accuracy would be compromised by working in Canadian dollars (C\$) [13]. Instead, U.S. Dollars are used exclusively and where needed converted for reference to Canadian dollars using a rate of C\$1 = 0.75\$ [13]. As such, these findings exclude currency exchange risk.

Accounting for the GHG emissions of the Athabasca oil sands

To account for the climate impact of the Athabasca oil sands, we use the metric of CO_2e per barrel of refined crude oil (CO_2e/bbl). We account for these GHG emissions by using three categories:

1. *incremental emissions*: the difference in GHG emissions between crude oil derived from the oil sands and the 2005 average GHG emissions of crude oil refined in the US;
2. *production emissions:* the total GHG emissions caused by production, upgrading, refining, and transportation of crude oil from the oil sands (well-to-tank); and
3. *total emissions:* the total GHG emissions caused by all steps from production through end consumption of crude oil from the oil sands (well-to-wheel).



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Oil Sands Information			**Reference**
Production	676,400,000	bbl/year	(Government of Alberta 2013)
Production Growth Rate	1.0%	Annual growth rate	*Assumed*
Well-to-Tank Emissions	172.3	kg CO2-eq/bbl	(IHS CERA 2012)
Well-to-Wheel Emissions	556	kg CO2-eq/bbl	(IHS CERA 2012)
Incremental Emissions	70.8	kg CO2-eq/bbl	*Calculated*
Electricity Intensity (Steam Extraction)	14	kWh/bbl	(AESO 2008)
Electric Heat Extraction	No		
Electric Heat Intensity	10	x multiplier of current	(AESO 2014)
Oil Sands Land Area	142200	(km)^2	(Government of Alberta 2015)
Maximum Turbine Density	1	turbine/km^2	*Conservative,* (Patel 2005)
Area for Wind Farm	50%	of total Oil Sands Area	*Assumed*
Total WTT Emissions	116.5	MT CO2-eq/yr	*Calculated*
Total WTW Emissions	376.1	MT CO2-eq/yr	*Calculated*
Total Incremental Emissions	47.9	MT CO2-eq/yr	*Calculated*

Conventional Oil 2005 US AVG			
Well-to-Tank Emissions	101.5	kg CO2-eq/bbl	(IHS CERA 2012)
Well-to-Wheel Emissions	487	kg CO2-eq/bbl	(IHS CERA 2012)

Wind Turbines			
Size	3.45	MW-peak	(Vestas 2014)
Capacity Factor	17%		(Natural Resources Canada 2013)
Capital Costs	1.71	$/W	(Wiser and Bolinger 2015)
Maintenance Costs	0.031	$/W/year	(EIA 2010)
GHG Emissions	10.4	g CO2-eq/kWh	(Raadal et al. 2011)
Life Expectancy	20	Years	(Nugent and Sovacool 2014)
Grid's Capacity for Wind	20%		(Georgilakis 2008)

Transmission Lines			
Cost	372	$/MW/km	(Delucchi and Jacobson 2011)
Aggregated Life Expectancy	40	years	(Delucchi and Jacobson 2011)
Redundancy Required	1	x	*Implicitly,* (Delucchi and Jacobson 2011)

Fig. 1. Input panel for the reconfigurable model, provided in the SM. Red cells are calculated values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Colloquially, we track three metrics corresponding to the three different levels of objections to the GHG emissions of oil sands: *first*, some people object to the higher emissions than conventional oil – *incremental emissions*. *Second*, others object to the emissions associated with production and refining of the oil altogether – *production emissions*. *Third*, others still object to the use of hydrocarbons altogether due to the emissions from extraction to end use – *total emissions.*

Among the many meta-analyses of the emissions of the Athabasca oil sands, we used the IHS CERA report because it was an independent report that used units per barrel of refined crude oil [14]. To aggregate the highly-varied estimates of the oil sands' emissions, we used IHS CERA's "average oil sands refined in the U.S. (2011)," which included emissions from production, upgrading, transport, refining, further transport, and the final product's combustion; it also accounted for the emissions associated with fuels used in production and upgrading of the crude oil [14]. The incremental emissions, production emissions, and total emissions used in our model were 70.8, 172, and 556 kg CO_2e/bbl, respectively [14].

The annual production of the oil sands was taken to be 676.4 million barrels per year [15], with a fixed annual growth rate of 1%. Given the volatility in global oil prices from late 2014 through 2015, one growth prediction was as credible as the next; 1% was chosen to ensure that the recommendations did not rely on the projected growth.

Accounting for the GHG emissions of wind turbines

Raadal et al. reviewed 22 papers that assessed the GHG emissions associated with 1–5 MW turbines; they found a range of 4–22 g CO_2e/kWh with a mean of 10.4 g CO_2e/kWh [16]. This simple number however neglects the strong dependency on the capacity factor, as does the model presented herein.

Emissions offsets for electricity generation

Wind energy generation has a net positive benefit on GHG emissions only when a generation technology that emits more GHG than wind can be turned off. In the case of this first-order model, we assumed that the GHG intensity of the generation technology that would be turned off would be the average GHG intensity of the region to which the power was transmitted. The scale of wind production proposed in this model required transmission over long distances to different regions. Our first-order model considered only five levels of resolution for the destination of the wind energy: onsite electricity usage, Alberta's grid, the rest of Canada, California, and the rest of the United States (Table 1).

Grid capacity

Because of the variability of wind power, a grid supplied by 100% wind from a single geographic location would be unstable. Electricity system operators compensate for this instability in two ways: first, by limiting the total percent of wind power they allow into their system; and second, by purchasing dispatchable generation to provide power when the wind is not blowing. This model does not account for the emissions associated with this dispatchable generation; it is therefore implicitly assumed to have the same GHG intensity as the region's existing generation mix.

The model dispatches electricity to different regions according to a user-definable transmission priority. When one region reaches its maximum capacity for wind power, here assumed to be 20% of produced power (not generation capacity) [17], the model starts to build transmission lines to the next prioritized option. Transmission priorities and the current fraction of wind supply in different grids are summarized in Table 1.

Transmission

Delucchi and Jacobson estimated the cost of high-voltage, long-distance power transmission to be $372/MW/km [27]. However, long transmission lines that are not grid-connected can pose serious issues if they are ever interrupted, as there is no method to dissipate the power. The modeling tool has a variable to allow lines to be constructed in duplicate, but the presented analysis does not include transmission duplication. Also, the emissions associated with transmission-line construction and transmission losses are left to a future version of the model.

Transmission stations are expected to have a lifetime of approximately 30 years, and transmission towers and lines may last for 50–70 years [27]. The first-order model assumed all transmission components last for the entire 40 year modeling timeframe.

Cost of wind turbines

We modeled the upfront capital costs of wind generation as inelastic and $1.71/W of nameplate capacity [22]. Wiser and Bolinger reported operation and maintenance (O&M) costs normalized by the total power generated; however, the EIA suggests that wind-turbine O&M costs are actually fixed and not variable [28]. To allow the model to be accurate over a wide range of capacity factors, we therefore used the EIA 2010 estimate for O&M of $0.031/W/year [28]. The life expectancy of a turbine was taken to be 20 years (the minimum estimate as summarized from literature by Nugent and Sovacool [29]).

Land area and turbine density

The Athabasca oil sands cover a geographic area of 142,200 km^2 [30], of which the Environmental Protection and Enhancement Act has approved 1444 km^2 for development by oil producers [31]. The model here assumes that 50% of the total geographic area of the Athabasca oil sands is available for use as a gigawatt-scale wind farm. Patel recommends that large wind farms be spaced 8–12 rotor diameters apart perpendicular to the prevailing wind, and 2–4 diameters apart in the direction of the prevailing wind [32]. The Vestas V126 has a rotor diameter of 126 m leading a minimum spacing of 1.3 turbines per km^2. Conservatively and to account for terrain variations, we therefore assumed the maximum turbine density to be 0.5 turbines per km^2.

Capacity factor

The RETScreen Software tool was used to convert average annual wind speeds into capacity factors using turbine power curve data [19]. We selected the Vestas V126 3.45 MW turbine as a reference turbine. More detailed power-curve data was available for the V126 3.3 MW version and this was used to generate the capacity factor, which was applied without modification to the 3.45 MW version. Using a wind-shear exponent of 0.2, the average found by Schwartz and Elliot [33], the capacity factor was determined to be 17% based on the average annual wind speed at Fort McMurray airport (2.7 m/s) [19].

Discount rate

To calculate the net present value of the costs associated with the proposed project, a discount rate was required. Cox and Murphy calculated the implied weighted average cost of capital for seven publicly-traded Canadian oil companies to be between 7% and 9% [34]. The model used the lower bound of 7% to be conservative (the model involves only expenses, so a higher discount rate improves the favorability proposed scheme).

Performance metrics

GHG Emission Metrics: The environmental benefits of the proposed solutions were assessed as the ratio of GHG emissions from the oil sands compared to the GHG offsets generated by the wind power. This ratio was calculated for the incremental, production, and total emissions. All three ratios (defined in Section Accounting for the GHG emissions of the Athabasca oil sands) were evaluated for a given moment in time (Instantaneous Carbon Ratio (Eq. (1))) and over the duration of the proposed project (Cumulative Carbon

Table 1
Capacity and GHG intensity of North American grids.

Location	Transmission Priority	Nominal Distance (km)	Average Yearly Load (GW)	GHG Intensity (MT CO$_2$e/GW-year)	Current Fraction of Wind-Generated Electricity
Onsite Usage	1	0	1.1 [see SM]	2.89 [see SM]	0% [see SM]
Alberta (AB)	2	500	9.1 [18]	7.54 [19]	4.3% [18]
United States (excluding CA)	3	5500	433 (467 including CA [20])	4.71 [19,21] (4.57 including CA [19])	4.7% (4.9% including CA [22])
California (CA)	4	2800	33.9 [23]	2.8 [24]	8.1% [23]
Canada (excluding AB)	5	4000	50.7 (59.8 including AB [25,26])	0.3 (1.6 including AB [19])	1.5% (2.0% including AB [25])

Table 2
Performance Metrics.

	Incremental Emissions	Production Emissions	Total Emissions
Instantaneous	Incremental Carbon Ratio	Production Carbon Ratio	Total Carbon Ratio
Cumulative	Incremental Cumulative Carbon Ratio (Incremental CCR)	Production Cumulative Carbon Ratio (Production CCR)	Total Cumulative Carbon Ratio (Total CCR)

Ratio (Eq. (2)) (Table 2). No discounting factor was used to distinguish between future and present GHG emissions.

$$\text{Instantaneous Carbon Ratio} = \frac{\text{Rate of GHG-emission offsets from wind power}}{\text{Rate of GHG emissions from the oil sands}} \quad (1)$$

$$\text{Cumulative Carbon Ratio}\,(t) = \frac{\frac{1}{t}\int_0^t (\text{Rate of GHG} - \text{emission offsets from wind power})\,dt}{\frac{1}{t}\int_0^t (\text{Rate of GHG emissions from the oil sands})\,dt} \quad (2)$$

Financial Viability Metrics: The financial viability of the model was assessed by considering two separate funding mechanisms: a per-barrel required investment, used to fund wind turbines, and a required reinvestment amount which levied an additional charge per kWh of generated power to fund turbine maintenance and additional turbines. We investigated investment amounts ranging from \$3–\$13/bbl, and reinvestment amounts from \$0–\$0.03/kWh$_{\text{wind}}$. An investment of \$3/bbl is equivalent to Alberta's 2017 carbon tax (C\$20/ton [2]) applied to the production emissions of the oil sands, while \$13/bbl is equivalent to the proposed 2018 tax (C\$30/ton [2]) applied to the total emissions. The upper limit on reinvestment charges was chosen to be \$0.03/kWh$_{\text{wind}}$ in order to maintain incentives for oil companies to keep the turbines spinning (2014 average wholesale electricity price in Alberta was C\$0.049/kWh [18]).

To evaluate cost effectiveness, the equivalent cost per ton of offset GHG emissions was taken as the net present value of all expenditures required from the oil company divided by the total offset GHG emissions. To keep the financial model clear, the investment required was presented in dollars per barrel of crude oil produced. A better system would base required investment amounts on accurately reported carbon emissions to incentivize innovation and emissions reductions.

Results

Instantaneous efficacy of wind power to offset GHG emissions

With sixteen thousand 3.45 MW wind turbines, the incremental GHG emissions caused by the oil sands as compared to conventional oil would be offset. This amount of electricity generation is equivalent to 105% of Alberta's electricity generation (Table 3), but in the model, the majority is sold to the U.S., where the GHG intensity of offset electricity is higher. With 71 thousand turbines (the maximum turbine density of one per two square kilometers), 410% of the incremental emissions can be offset, which is equivalent to 168% of the production emissions or 52% of the total (production and end-use) emissions (Table 3). Increasing the number of turbines by 440% (from 16 to 71 thousand) only increased the offset emissions by 410%. This non-linearity arises because smaller ACT projects are able to offset power from the most GHG intensive electricity grids; conversely larger ACT projects saturate the most GHG intensive grids and have to also offset electricity production from less GHG intensive sources.

Beyond the land area constraints, the model also shows that if Canadian and American grids can only handle 20% wind energy (currently 2% and 4.9% respectively, Table 1), 88% of the total annual emissions of the oil sands production and consumption could be offset with wind power (Table 3). Importantly, this shows that if GHG emissions from other hydrocarbon sources are to be offset by renewables, the grid must be able to handle significantly more renewable energy, which would also require a significant amount of energy storage devices and a modern grid for delivering power produced anywhere it is generated to anywhere it might be needed.

Cumulative efficacy and financial feasibility

To efficiently summarize the scheme's performance, results are presented for the Athabasca region's wind capacity factor of 17% alongside results (in parentheses) for a more traditional project's capacity factor of 30%. The reader is reminded that the *Incremental*, *Production*, and *Total* metrics respectively account for: the relative GHG intensity of the oil sands compared to conventional oil extraction, the GHG emissions from production and refinement of oil sands oil, and the total emissions including end use.

With a capacity factor of 17% (30%) and feasible investment and reinvestment amounts, the maximum possible Incremental CCR (Eq. (2)) was 128% (309%) (Fig. 2). It was therefore possible to mitigate the incremental/additional GHG emissions of the oil sands as compared to conventional crude oil, but only possible to achieve a Production CCR of 53% (127%) and a Total CCR of 16% (39%).

Table 3
Instantaneous model of wind turbine impact.

	Scenarios			
	Incremental Offset	Production Offset	Max Density	Saturating the Grid with 20% Wind
Turbines Built (Thousands)	16	42	71	139
Turbine Density (#/(km)^2)	0.11	0.29	0.50	0.97
Wind Turbine Cost (\$ Billions)	96	246	419	818
Transmission Cost (\$ Billions)	10	27	48	97
Name Plate Capacity (GW)	56	144	245	478
Generation (GW)	9.6	24.4	41.7	81.3
Wind Turbine Emissions (MT CO$_2$e)	1	2	4	7
Annual Carbon Offset (MT CO$_2$e)	48	117	196	330
Incremental Carbon Ratio	100%	243%	410%	689%
Production Carbon Ratio	41%	100%	168%	283%
Total Carbon Ratio	13%	31%	52%	88%
Percent of Alberta's Generation	105%	269%	458%	894%
Percent of Canada's Generation	19%	48%	82%	160%

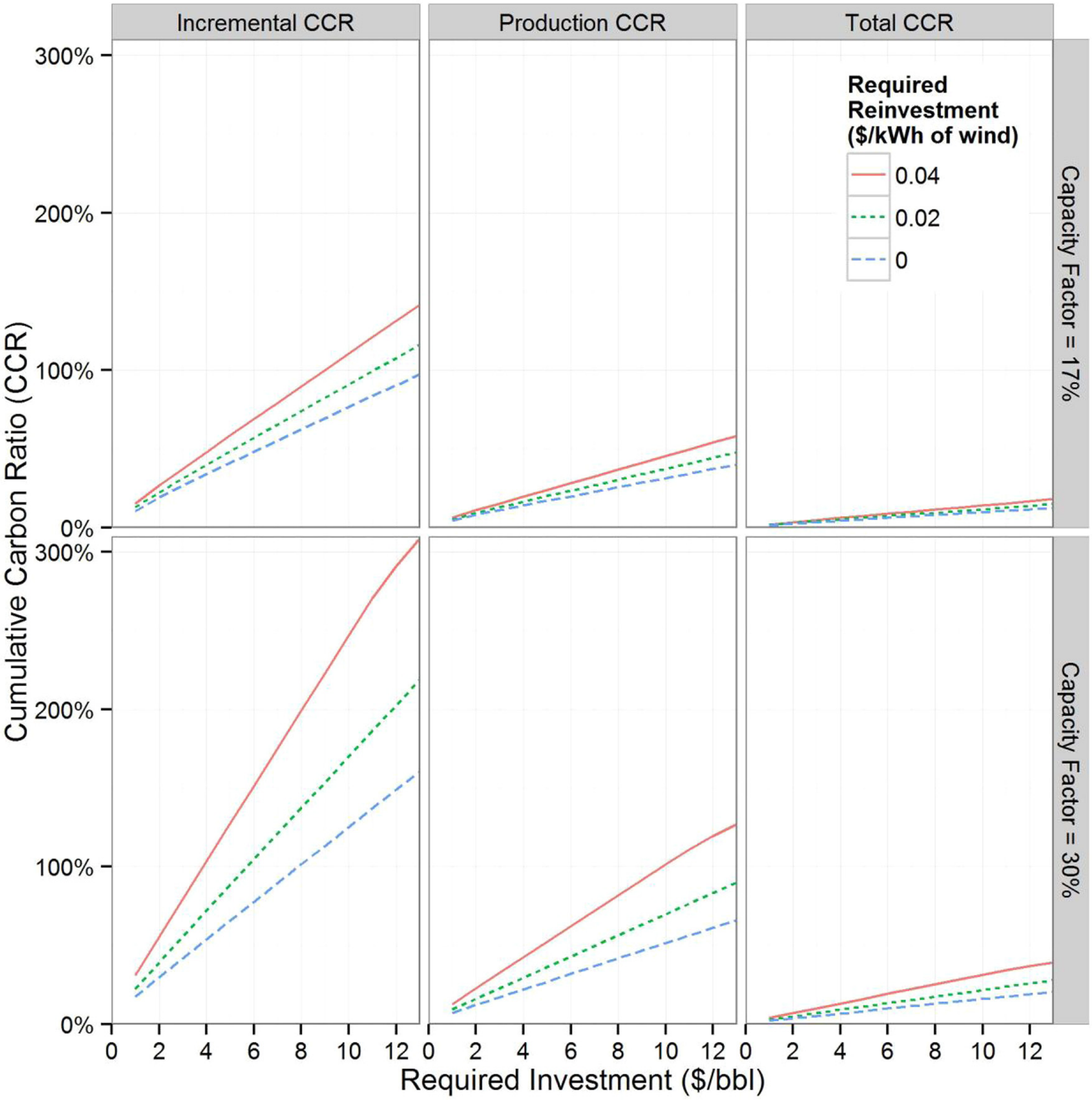

Fig. 2. The model's cumulative carbon ratio (CCR) after 40 years with different investment and reinvestment rates. The two rows of this graph show how the model changes for the expected capacity factor of 17% [Top Row] and for a more typical capacity factor for wind projects (30%) [Bottom Row]. Each column summarizes a different CCR metric: Incremental – additional emissions of oil sands as compared to conventional oil [Left], Production – the emissions from production and refinement [Center], and Total – all the emissions from production to end use [Right].

Given the feasible range of parameters, to achieve an Incremental CCR of 100%, the lowest reinvestment rate possible was $0.003/kWh$_{wind}$ (none needed) accompanied by an investment of $13/bbl ($7.90/bbl) (Fig. 2). The lowest possible per barrel rate was $10/bbl ($4.70/bbl) accompanied by a reinvestment of $0.03/kWh$_{wind}$ ($0.03/kWh$_{wind}$) (Fig. 2).

A moderate reinvestment rate from electricity sales from the wind farm of $0.015/kWh$_{wind}$ and an investment of $12/bbl achieved an Incremental CCR of 103% (187%) (Fig. 2). This scheme will be the focus of the remaining analysis. While this balanced funding scheme finished with a total of 33 (37) thousand active wind turbines (Fig. 3), the land area could have supported 71 thousand turbines. The lifespan of the turbines sharply limited the ability for the model to expand after 20 years (Fig. 3). Designing turbines with longer life expectancies would increase the benefits of any wind farm proposal, including this one.

Importantly, these results demonstrate that the proposed scheme can offset the incremental GHG emissions of the oil sands and that these benefits can be realized with investments of $10-$13/bbl, even with a capacity factor as low as 17%. Further, with wind turbines located in a region with a capacity factor of 30%, investments of $12–13/bbl could offset the entire production emissions of the Athabasca oil sands.

The above comparison of the proposed scheme with its capacity factor of 17% against a more typical 30% demonstrates that, while mitigating the incremental emissions of the oil sands is important, far greater GHG mitigation benefits can be derived from investing the funds in a similarly scaled project in a windier location.

Relative efficacy of wind turbines located with the Athabasca oil sands

The net present cost of this scheme is $146 billion and it offsets a total of 2.5 GT of CO_2e; it therefore has a net efficiency of $59/ton CO_2e (Fig. 4). The proposed scheme therefore costs 55% more per ton of offset CO_2e than other estimates for high-penetration wind power in the U.S. Even less favorably, the scheme's costs are double

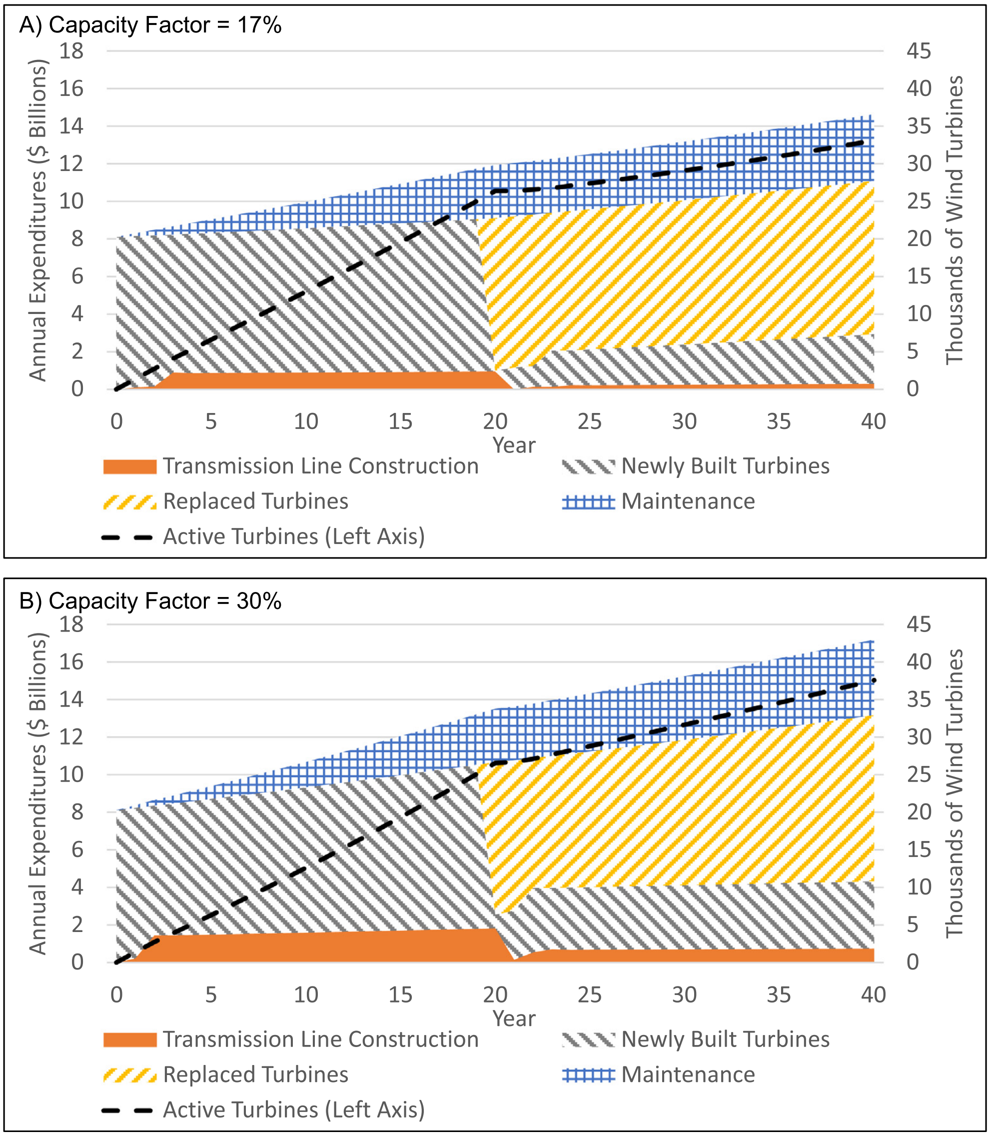

Fig. 3. The annual expenditures [Left Axis] and the number of active wind turbines [Right Axis] for the proposed scheme with 17% capacity factor [Top] and a capacity factor of 30% [Bottom], charging $\$12$/bbl and $\$0.015/\mathrm{kWh}_{\mathrm{wind}}$.

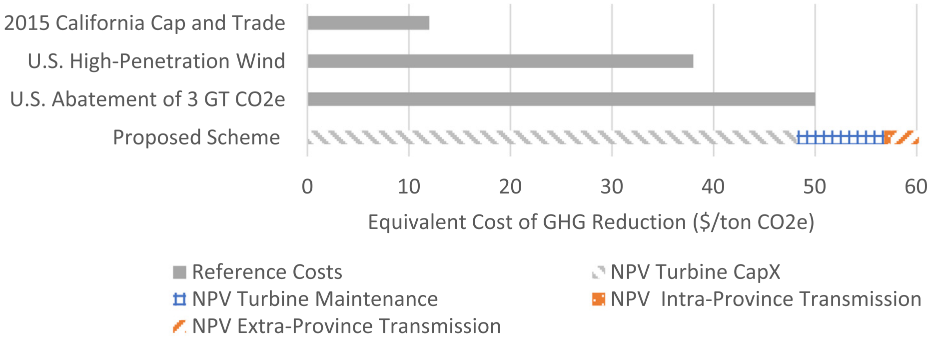

Fig. 4. Equivalent cost of GHG reduction (at 17% capacity factor), using the net present value (NPV) of future expenditures and separating the cost into capital expenditures (CapX), turbine maintenance, transmission line construction within Alberta (intra-province transmission), and all other transmission line construction costs (extra-province transmission). Reference costs are for 2015 Cap and Trade pricing in California [7], high-penetration onshore wind [8], and the maximum cost to achieve an annual abatement of 3000 MT/CO$_2$e per year in the U.S. [8].

the proposed Albertan carbon taxes and five times California's current cap and trade prices (Fig. 4). This result however, is highly sensitive to the input discount rate.

The largest cause of the proposed scheme's inefficiency is the wind turbines' low capacity factor. Had there been a more typical capacity factor of 30%, the efficacy would have been $35/ton

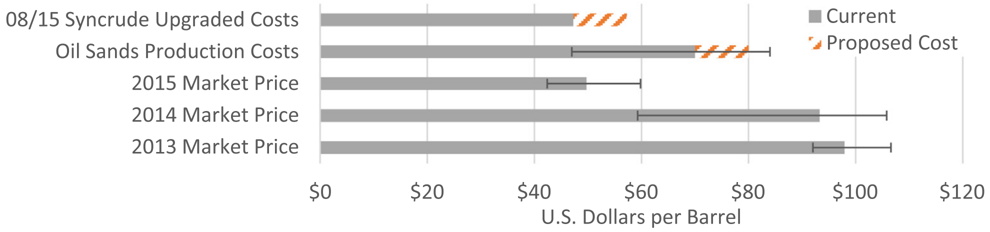

Fig. 5. The production cost of upgraded oil from the oil sands [5] compared to the market price [4] in 2013, 2014, and 2015, where error bars show the monthly minimum and maximum prices and the uncertainty in production cost estimates. Production costs also show the proposed addition of a $10/bbl tariff.

CO_2e, close to Creyts et al.'s high-penetration wind estimate of $38/ton CO_2e [8]. This improved capacity factor would make it possible to achieve a Production CCR of 108%, and should such a location exist, it should be pursued (Fig. 2). Interestingly, with this higher capacity factor and over a larger range of investment and reinvestment values, the model exhibits nonlinearities, which make the reinvestment rates more important than the investment rates (Fig. SM-1). In addition to proving the scheme's viability under higher wind speeds, the agreement with published estimates helps to validate the model.

With a wind capacity factor of 17% in the Athabasca region, turbine installation and maintenance accounted for 94% of the costs ($55/ton CO_2e) (Fig. 4) – despite transmitting power across the continent. This is a surprising and important result; it suggests that the distance to the consumer is less important than the capacity factor available at the wind farm site and that alternate sites for the proposed scheme should be considered. This conclusion must however be qualified by the fact that the cost model for transmission capacity does not capture the interaction between capacity factor and transmission costs.

When crude oil prices are as low as 2015 values, adding $10-$13/bbl to the production costs of crude oil is not feasible (Fig. 5). However, should markets rebound to 2013 prices, there would be enough of a margin to support the proposed scheme, even if it is not optimally located (Fig. 5). Locating the proposed scheme somewhere with higher wind speeds would be even more promising.

Broader application of the ACT concept

The above study showed that when the alternative to carbon taxes is applied to a wind resource located in a 30% capacity factor area, after four decades the carbon impact of extracting hydrocarbons can be completely mitigated. In even higher capacity factor regions, which can also be obtained with taller towers, a proportional increase can be expected. Such a scheme would enable a steady evolution of the hydrocarbon industry and its associated jobs into a renewable focused industry. With this in mind, other applications of ACT that might be considered include coal mining and pipelines[1].

The results presented in Section Instantaneous efficacy of wind power to offset GHG emissions showed that if the ACT were widely applied, then as renewables' percentage of total electricity production increased, additional energy storage would be needed. For example, one contemporary topic is putting miners back to work. More contentious than coal mining itself, is one common mining method – mountain top mining where the top of the mountain covering a seam is removed, and the coal dug out. Taking a symbiotic view of these two issues [35], one can envision employing miners to not only take off the top of the mountain and dig out the coal, but also using the overburden to create dams for a lower reservoir and an upper reservoir from where the coal was in order to create a pumped hydroelectric storage project. Not only would this provide additional (and less GHG intensive) employment for local miners, but the storage they create would facilitate an expansion of domestic wind production. Since many large turbine elements are made in nearby Midwestern states, additional jobs in energy industries would be created with the gradual evolution to a renewable energy industry focus and a net zero carbon footprint over the period of evolution.

Another form of renewables investment is energy and fresh water by desalination. Californians mandate renewable energy and energy storage yet thirst for fresh water as the long-term drought threatens the Southwest. An Integrated Pumped Hydro Reverse Osmosis (IPHRO) system [36] could provide all the power and fresh water needs for all of Southern California and Mexico. This type of system will require power input from renewable energy sources, which could be financed by the ACT. Note that Southern California's economy has a long history of economic enhancement by local oil production and refining.

Pipelines are another often contentious topic, with the potential for pollution in the event of a spill being most difficult to address. Again a symbiotic approach can be useful. For example, along many of the pipeline routes in the middle of the U.S. through prime farmland, there is also excellent wind potential, so a portion of pipeline income could be invested in wind turbine development along the pipeline route in addition to a transmission line system along the same right of way to bring the power to where it is needed. This would also bring much needed income to farmers, especially given low commodity prices and uncertain weather including drought [37]. However, with any pipeline there is the potential for leaks which farmers and others fear will poison aquifers used for irrigation. Fortunately history teaches that double hull oil tankers solved most spill problems and did not cause financial devastation to the tanker or oil industry [38]; thus if an oil pipeline was contained within an outer pipe or tunnel, the space between could be monitored for leaks, and any leak would simply be channeled to periodic check/collection points.

As ACT investments ramp up, the need for skilled workers to build the renewable energy systems and components will increase, and should be coordinated with workforce-training programs, financed with local and federal job training funds, especially in job starved inner city regions. In more rural areas, where many wind and solar energy farms will be built, the need for skilled heavy equipment operators and renewable energy machine installers and maintenance people will also require training programs. With good planning, a skilled workforce would be in place to commence construction of ACT financed plants with significant sourcing of domestically manufactured solar panels and wind turbine components.

Even if hydrocarbon-based production companies can see an acceptable internal rate of return on opting for participating in the ACT, some may question why they should invest in their com-

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[1] This would require evolution of the spreadsheet provided in the SM to address site and project specific issues and boundary conditions.

petition? The answer is simple: History. Many a number of well-known firms have failed or withered from Polaroid to RCA to Kodak and many more large and small. A solution appears to be an ambidextrous approach to overcome being trapped by past successes: "Firms must remain competitive in their core markets, while also winning in new domains" [39]. In the case of energy companies, BP may have had it right when before the last oil boom it had renamed itself "Beyond Petroleum" and Arco Oil & Gas had a solar division. But science and engineering are driven by the unstoppable force of human curiosity, and companies and even nations that fail to understand this are destined to wither so history proves.

Conclusions and recommendations

Wind energy co-located with the Athabasca oil sands was found to be able to offset the incremental GHG emissions with investments ranging from $10–13/bbl, in spite of a very low regional wind capacity factor of 17%. However, given 2015 oil prices, $10/bbl is not feasible unless the environmental concerns, which limit industry growth, were quantified and included in the model. Independent of its affordability, the proposed wind project was found to cost 55% more per ton of offset GHG than typical on-shore wind projects due to the low wind speeds. Therefore, we recommend that alternate sites for this wind project be found; should such sites have capacity factors of 30% or more, we expect the re-sited scheme to require only $5/bbl to offset the incremental emissions of the oil sands. Further, such a re-sited scheme could offset the total production emissions for $12/bbl.

Despite our recommendation not to site a massive wind farm in the Athabasca region, the ACT scheme and the reconfigurable modeling tool presented in this paper holds promise for three reasons: *First*, were crude oil producers (through wind energy companies) able to secure high wind capacity factor land-use contracts in southern Alberta for a reasonable price, the capacity factor would increase and the viability of the project would dramatically increase. *Second*, in other locations of large-scale extraction where average wind speeds are higher, such as in North Dakota, the reconfigurable modeling tool could be applied to efficiently evaluate the viability of co-located wind power schemes. *Third*, oil prices have been high, then low, and then high again in the past, and will likely go up again, so planning could be based on a longer-term average.

This work has validated the notion that many gigawatts of wind power can offset the incremental GHG emissions of the Athabasca oil sands and that such a scheme can be realized with investments as low as $10/bbl, which the oil companies would maintain on their books as profit-bearing assets. Additionally, this work demonstrates a new top-down method of analyzing large-scale proposals for reducing GHG emissions and provides readers with a reconfigurable model, which can help understand when and where the proposed alternative scheme could best be applied. We strongly recommend that alternate sites, such as discussed in Section Broader application of the ACT concept, for large renewable energy systems financed by an ACT be explored and pursued immediately to help companies and their employees evolve from a hydrocarbon to a renewable energy focus, while hastening the day the energy sector becomes dominantly based on renewables.

The technologies for renewables are at a tipping point [40], and some would say when properly accounted they are more economical than even burning gas in many cases [41]. Furthermore, the Paris Climate Agreement empowers nations to tax the carbon content of all goods without fear of retaliation. A new race is on, and as countries race to create jobs and build strong low carbon economies, they would do well to note that a Tesla Model S has greater acceleration than any standard *Gas Guzzler* [42]:

Yeah, I got a gas guzzler,
I ain't no nature loving, tree hugga,
I'm a red blooded American baby,
Conserve energy, is ya crazy?
I'm in my big body truck,
Windows down wit the AC up,
To the max, stressin' out the compressor,
You ain't never gon' catch me in a Tesla!

Ain't complainin', just sayin,
World's changin', pain's stayin'
While they gainin', we can't grow,
Need a turbine wherever the wind blows

I got my yoga mat, and my nap sack,
Granola snack, and Subaru Outback,
Neva slack, I get down to the nitty gritty,
Carbon footprint like the founder of Solar City,
Pity the planet do my best to try to salvage it,
Eat fruit and salad counterbalancin' for savages,
The law of averages, analysis of risk,
Make me wish that I was ignorant, cause ignorance is bliss!

Ain't complainin', just sayin',
Spring without rain? Different ballgame,
Climate change, should go slow,
Get coal miners buildin' pumped storage hydro

Persistent, and mount the resistance,
E'ry day, e'ry ounce of my existence,
On the real, exactly how I feel,
I ain't got a dollar bill for your windmill,
I got a license, so I'm licensed,
To burn petroleum like incense,
Sacrificin' and payin' high prices,
Who I look like, Neil Degrasse Tyson?

Ain't complainin', just sayin,
World's changin', pain's stayin'
While they gainin', we can't grow,
Livelihood, the seed we need to sow

We're so close, to disruptin' the Cosmos,
Real talk, it ain't tweet or a blog post,
Talk Radio hosts, boast about the tenth amendment,
Missin' signs that we're steps away from Armageddon,
Livin' like this ain't livin', barely survivin',
Divin' head first in an empty pool, with closed eyes, and
Hopin' that we do not die is only settin' up a trap,
When the polar caps melt, it's a wrap!

Ain't complainin', just sayin',
Winters without snow, continuin' in a row,
Glaciers meltin', there's work in stoppin' the flow,
Instead of wonderin', where did my job go?

We all want milk and honey, but need a fair price,
So let's share in the fight, as some have less to sacrifice,
Buildin' devices everywhere except America,
An unrighteous crisis that divides us in hysteria,
But we can all agree, we need new factories,
Focus our "energy", form solar cells in US cities,
Carbon free power plants and trees grown in the heartland,
World peace and pride where we reside will make us great again!

Ain't complainin', just sayin',

Keep prayin', but stop delayin',
World ain't waitin', for us so,
Lead the way off the tightrope to a path of hope!
[Marc Graham and Alexander Slocum (2016)]

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.seta.2017.01.003.

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