**Methods**

*Accounting for the GHG Emissions of Oil Sands*

To account for the climate impact of the Canadian oil sands, we use the metric of kg CO2,eq/bbl of refined oil. We account for these GHG emissions in three categories:

1. the incremental emissions caused by the carbon intensive production, upgrading, refining, and transportation of oil sands, as compared to the 2005 average GHG emissions of oil refined in the US;
2. the total GHG emissions associated with production, upgrading, refining, and transportation of oil (well-to-tank); and
3. the total GHG emission from production through end consumption (well-to-wheel).

Studies vary up to 30% on the emissions of even a single type of crude oil [1]. Further complicating the matter, the GHG emissions of different oil sands extraction techniques, upgrading processes and quality of the oil can add up to almost 100%. Instead of adding to or choosing between the existing and vast literature on this topic, we built a Microsoft Excel-based tool to help policy makers, industry analysts, and researchers determine the potential benefits of the solutions proposed in this paper. The results presented in this paper use IHS CERA’s estimate for the emissions of the average oil sands refined in the US in 2011, using a wide system boundary, but the modeling tool is provided (as-is) in the Supplemental Information available online.

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| --- | --- | --- | --- |
| GHG Emissions of the Oil Sands (Kg CO2,eq/bbl) | Incremental | Well-to-Tank | Well-To-Wheel |
| **“Average oil sands” (2011) wide boundary [1]** | **70.8** | **172.3** | **556** |
| “Average oil sands” (2011) narrow boundary [1] | 52.9 | 140.4 | 525 |
| Canadian Oil Sands: SAGD SCO (wide boundary) [1] | 111.3 | 212.8 | 598 |
| Canadian Oil Sands: Mining Dilbit (narrow boundary) [1] | 9.3 | 96.8 | 482 |
| AVG 2005 for oil refined in the US (narrow boundary) | -- | 87.5 | 473 |
| AVG 2005 for oil refined in the US (wide boundary) | -- | 101.5 | 487 |

For reference, Table Y summarizes the average and extreme values for the emissions summarized by [1]. The incremental value was calculated as the difference between a given process and the average US barrel refined in the US. Emissions values calculated with a “wide boundary” were accordingly compared to the 2005 average values calculated with a similarly “wide boundary.” While there are many available meta-analyses, we selected to use the values from IHS CERA because it was generated as an independent report and uses units of per barrel which are useful for the first-order model presented herein.

*Accounting for the GHG Emissions of Wind Turbines*

Again the focus of this study was not to accurately quantify the GHG emissions of wind turbines but to provide a decision-making tool. ~~Weisser’s review of 15 life cycle assessments of wind turbines concluded that onshore wind had an equivalent carbon emission ranging between 8 and 30 gCO~~~~2~~~~eq/kWh (electricity I think).~~ Raadal et al. reviewed 22 papers that assessed the GHG emissions associated with 1-5MW turbines; they found a range of 4-22 with a mean of 10.4 g CO2-eq/kWh [2]. This simple number however neglects the strong dependency on the capacity factor. Steel and concrete production account for the largest components of this carbon impact.

*Emissions Offsets for Electricity Generation*

Generating electricity is only helpful when the generation of that power means that a more harmful generation technology can be turned off. The climate impact of adding wind turbines in a country with only hydro power is evidently different than in a country with only coal power. Further, the scale of wind production proposed in this model is extremely large and requires major power transportation outside the region where it was produced. As a first-order model, we considered four levels of resolution for carbon offsetting:

|  |  |  |
| --- | --- | --- |
| Location | Representative Distance (km) | GHG Emissions of Generation Mix |
| Onsite Usage | 0 | *Cogen: as a first estimate, 40% to electricity, 50% to usable heat with 10% loss[[1]](#footnote-1). Therefore 75% efficiency NG source of electricity generation. NG taken at 45% as an average between 35-42 for simple cycle and 52-60% for combined cycle* |
| Alberta | 500 |  |
| California | 2800 |  |
| Canada | 4000 | 85 Mt in 2013 [NIR report] to elec gen |
| United States | 5500 |  |

In Canada, official, regional, GHG emissions are reported with electricity and heating sources combined. To normalize for this, we instead used the mean GHG emissions associated with different supply types [3] and scaled these by the official generation mix numbers.

*Grid Capacity*

Because of the variability of wind power, a grid supplied by 100% wind from a single geographic location would evidently 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 supplement when the wind is not blowing. This model does not account for the emissions associated with this dispatchable generation; it is implicitly therefore assumed to be equivalent to the baseline generation mix. The capacity of reach regional unit and the additional wind percentage it will allow was taken as input to the model. The presented results assume that 20% wind power is an acceptable ratio.

|  |  |  |  |
| --- | --- | --- | --- |
| Location | Representative Distance (km) | Average Yearly Load (GW) | Current Wind Fraction |
| Onsite Usage | 0 | 1.1[[2]](#footnote-2) | 0%[[3]](#footnote-3) |
| Alberta | 500 | 8.8 [5] | 7% [5] |
| California | 2800 | 33.9 [6] | 8.1% [6] |
| Canada | 4000 | 71.6 [7] - 8.8 [5] = 62.8 | 1.6% [7] [0.8% w/o Alb] |
| United States | 5500 | 467 [8] - 33.9 [6] = 433.1 | 4.2% [8] [3.9% w/o Cali] |

*Transmission*

Delucci and Jacobson found that the cost of high power transmission lines ranged from $299-$429/MW/km of transmission capacity; their mean value was $372$/MW/km [9]. Long transmission lines that are not grid-connected can pose serious issues if they are ever interrupted as there is no method for the power to dissipate; previous proposals to export power from the oil sands to California have failed to overcome this issue [Ref needed]. Off-shore wind farms overcome this by requiring independent transmission lines to account for the possibility of one of them failing. Delucci and Jacobson did not account for this, but this factor is a variable in the Excel model and is taken as 2 for the results presented.

Transmission stations are expected to have a lifetime of approximately 30 years, while transmission towers and lines may last for 50-70 years [9]. The details of this modeling were beyond the scope of this proposal and so the built transmission capacity was assumed to last for the 40 year modelling window. The incremental emissions from transmission line construction and the losses incurred in transmission are left to a future version of the model.

*Cost of Wind*

We modeled the upfront costs of wind generation as US$5/MW, annual maintenance as 5%.

**References**

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[3] D. Weisser, “A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies,” *Energy*, vol. 32, no. 9, pp. 1543–1559, Sep. 2007.

[4] AESO, “Future Demand Outlook,” Alberta Electric System Operator, 2008.

[5] AESO, “AESO 2014 Long-term Outlook,” Alberta Electric System Operator, 2014.

[6] California Energy Comission, “Total System Power,” *Energy Almanac*, Seot-2015. [Online]. Available: http://energyalmanac.ca.gov/electricity/total\_system\_power.html. [Accessed: 21-Sep-2015].

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[9] M. A. Delucchi and M. Z. Jacobson, “Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies,” *Energy Policy*, vol. 39, no. 3, pp. 1170–1190, 2011.

1. <https://www.clarke-energy.com/chp-cogeneration/> [↑](#footnote-ref-1)
2. Calculated based on 1.9 bbl/day [1] and 14 kWh/bbl [4] [↑](#footnote-ref-2)
3. No wind installed in Northeast or Northwest [5] [↑](#footnote-ref-3)