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statement

Greenhouse gas footprints of different oil feedstocks

Summary

In future, road transport will be required to make a stronger contribution to the reduction of greenhouse gas (GHG) emissions in the European Union (EU). How to account for the different GHG footprints of transport fuels derived from different sources of fossil oil feedstock is a contentious issue and was extensively debated in the context of proposed amendments to the EU Fuel Quality Directive. One aspect related to the life-cycle assessment of the GHG emissions of transport fuels derived from oil sands, but a broader issue was the extent to which GHG footprints varied both within and across various categories of feedstock. EASAC therefore decided to examine both issues.

On the specific issue of oil-sands-derived fuels, the expert advice received by the European Commission in 2011 appears sound in the light of the latest information; GHG emissions from oil-sands-derived fuels are estimated to be higher than when fuels are derived from an average of the EU's conventional oil feedstocks. However, even in the latest life-cycle assessments, some factors remain excluded and would need to be included to enable full comparisons to be made.

Recent data have also brought into focus the wide range of GHG emissions from both 'conventional' and 'unconventional' sources of crude oils. These data make it more difficult to justify on scientific grounds the allocation of 'average' values for different categories of feedstock ('conventional', 'natural bitumen', shale oils', 'coal to liquid' and 'gas to liquid') which was one option debated in relation to the calculation methods and reporting requirements for Article 7a of the Fuel Quality Directive.

With respect to future policy development, EASAC comments that:

- Differentiating between oil feedstocks of different GHG intensity is appropriate if global emissions from the EU transport sector are to be properly accounted for, and for EU purchase decisions to deliver market signals to influence investment decisions and innovation priorities towards lower carbon sources of crude oil.
- While the allocation of responsibility for accounting for emissions between oil users and producers remains a political question, transparency of reporting on the GHG emissions of different sources of oils is important for decision-making.
- The EU's upstream emissions reduction (UER) scheme or other measures should encourage those who are responsible for future investment decisions to sufficiently take into account the GHG intensity of the fuels which are to be produced by the projects.
- The major limitation when applying climate-based policy measures to transport fuels remains the lack of reliable information from feedstock producers, since operators in many regions of the world are often not subject to formal data publication requirements.

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1. Background

Road transport accounts for 20% of the overall greenhouse gas (GHG) emissions in the EU. The EU is committed to at least an overall 40% reduction in GHG emissions by 2030 as one of the five pillars of its Energy Union[1] framework strategy, and transport is clearly required to make a substantial contribution; indeed, the 2011 White Paper foresees a target of a 60% reduction by 2050 for road transport (EC, 2011). Among other measures, the EU adopted the Fuel Quality Directive in 2009 where Article 7a sets a target to reduce the GHG intensity of transport fuels by 6% by 2020 (EC, 2009). This Directive recognises that the oil feedstock for transport fuels can be categorised according to its origin and proposed the categories of 'conventional', 'natural bitumen' ('oil sand'), 'shale oils', 'coal to liquid' and 'gas to liquid'. Because of the differences in energy required in separating and/or processing, GHG emission intensities (footprints) may differ between categories.

How to account for such differences in GHG footprints has been a contentious issue. Debate on implementing Article 7a of the Fuel Quality Directive focused on how the GHG emissions of transport fuels derived from different categories of feedstock could be reliably and cost effectively determined, and/or 'default values' assigned to each category. After extensive consultation and expert advice, the Commission published an 'impact assessment' summarising four main options, and detailing the steps taken to identify the preferred approach (EC, 2014). Options to assign average default values for GHG intensity to each category, or to require suppliers of transport fuels to take into account the GHG intensities of their original feedstocks in their emission inventories, were investigated, and found to introduce a competitive disadvantage to higher intensity feedstocks. These options were not pursued and suppliers of transport fuels are now required merely to submit reports using a single default GHG intensity value for each type of fuel (gasoline, diesel) based on the average of the EU fossil fuel mix (EC, 2015).

While there is no need for suppliers to differentiate between feedstocks of low or high GHG intensity, the Directive does introduce Upstream Emission Reductions (UERs) to 'incentivise suppliers to reduce the greenhouse gas intensity of transport fuels' (EC, 2015). UERs will be awarded to suppliers who reduce the GHG intensity of the fuels they supply and UER credits will be tradable in line with the EU's Emissions Trading Scheme. They are, however, expected to be earned largely through reductions in flaring and venting (ICCT, 2014) rather than by reducing GHG intensities through the introduction of less energy-intensive extraction processes.

The 2015 amendment to the Fuel Quality Directive aims to deliver the transport sector target of 6% reduction in GHG emissions by 2020, and will not be revised before then. The Commission has also stated that it does not plan to establish new targets for the GHG intensity of fuels in the transport sector after 2020 (EC, 2014a). However, since then, undertakings have been made by all parties at COP21 to update each five years the pledges which have been made to limit emissions. Pressure to find additional means of reducing GHG emissions from all sectors thus remains, and options for reducing GHG emissions from the transport sector are likely to remain on the agenda.

There are two science-based issues here: firstly the role of life-cycle assessment in estimating the GHG intensity of different fuels from different sources; and secondly the scientific evidence on the extent to which these intensities vary both within and across various categories of feedstock. EASAC therefore decided to examine both issues to support debate on future transport fuels policies. EASAC's analysis of the adequacy and complexity of life-cycle assessment focuses particularly on the literature that has been published on fuels derived from oil sands. EASAC's analysis of the variations within and between different feedstock categories focuses on recent data published on conventional oil and shale oil. In this statement therefore, we first treat the GHG footprint of oil sands in some detail before including updated information on other sources. We conclude with a commentary by EASAC on the policy implications of the latest scientific evidence.

2. GHG emissions from oil-sand-derived fuels

Since oil sands have been producing increasing amounts of 'unconventional' oil[2], these became a particular focus of debate on the Fuel Quality Directive

[1] The European Council Conclusions on the Energy Union (19 March 2015) state that 'The EU is committed to building an Energy Union with a forward-looking climate policy on the basis of the Commission's framework strategy, whose five dimensions are closely interrelated and mutually reinforcing (energy security, solidarity and trust; a fully integrated European energy market; energy efficiency contributing to moderation of demand; decarbonising the economy; and research, innovation and competitiveness)'.

[2] Canadian oil sands production was 1.95 million barrels per day (310,000 m^3/day) in 2013 and had been projected to grow to 4.81 million bpd by 2030 (765,000 m^3/day) (http://www.capp.ca/publications-and-statistics/publications/247759) before the fall in oil prices during 2014/5.

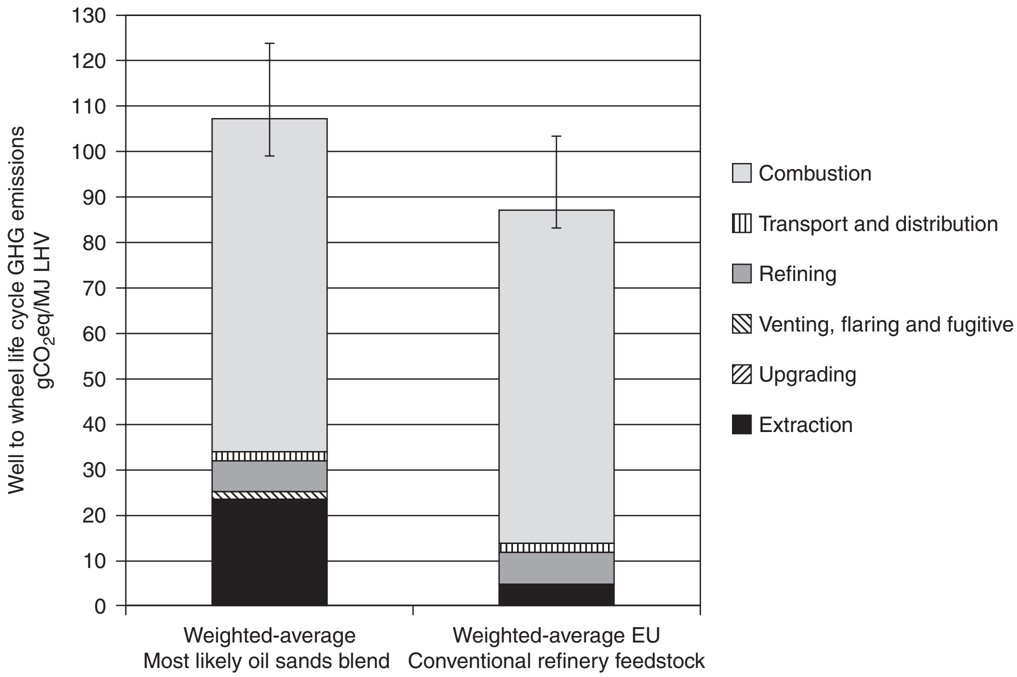

Figure 1 Petrol WTW emissions derived from oil sands compared with conventional EU refinery feedstock. Chart bars represent the most likely estimates; low and high ranges are represented by vertical bars. (Brandt, 2011).

amendments already mentioned, with the central technical issue being the extent to which their GHG emissions were higher than conventional sources of crude oil. One study commissioned by the EC in 2011 concluded that the well-to-wheel (WTW) life-cycle emissions for petrol from oil sands were *on average* ~23% higher than when the fuel comes from a production-weighted average[3] of the EU's conventional refinery feedstock (Brandt, 2011). This ~23% higher value' was, however, contentious since the average values for both oil sands and conventional sources included a wide range of individual values, so that there was overlap between the highest-emitting conventional source and the lowest–emitting oil sands source. We thus start by examining the life-cycle assessment process and its assumptions and update the 2011 conclusion.

The procedures used for determining the GHG emissions associated with different methods of oil sands extraction and processing are described in the Annex. In the Commission's original study, different analyses generated a range of estimates for GHG emissions which are shown in Figure 1 (Brandt, 2011). This shows (in the left hand column) the *most likely*[4] industry-average GHG emissions from petrol derived from oil-sands-derived feedstock (107.3 gCO_2eq/MJ), together with bars which show the spread of values from different life-cycle assessment studies. Emissions from oil-sand-derived fuels can be seen to be higher than the *most likely* industry-average GHG emissions from conventional fuels (87.1 gCO_2eq/MJ) in the right hand column by ~23%.

The studies reviewed by Brandt (2011) included different assumptions and boundaries[5], and research has been published since, reducing some of these uncertainties. On land use change, Yeh et al. (2014) estimated that the production-weighted land use GHG emissions were 3.38-3.43 gCO_2eq/MJ for surface mining (1985–2009) and 1.78–2.80 gCO_2eq/MJ for *in situ* production - higher than estimated by Brandt (2011). Englander et al. (2015) analysed facility-level energy consumption and environmental emissions data which had been collected for 24 operating projects (seven mining projects and seventeen *in situ* projects) over the period 2005–2012 (mining) and 2009–2012 (*in situ*). The results of this research have been used in an updated calculation (Cai et al., 2015) of GHG intensity across the whole life cycle (well to

3 'Weighted averaging' takes into account the production pathways involved and their relative contribution.

4 Brandt (2011)'s 'most likely' figure for the mix of product imports was not an average of high and low but assumed that there would be some disincentive to high-emitting sources and that projects having characteristics similar to the high case were less likely to be constructed.

5 For instance, differences emerged from the following:

- assumed efficiencies of extraction and upgrading;
- the fuel mix assumed to be consumed during extraction and upgrading;
- treatment of secondary non-combustion emissions sources (venting, flaring, etc.);
- ecological emissions such as from land use change.

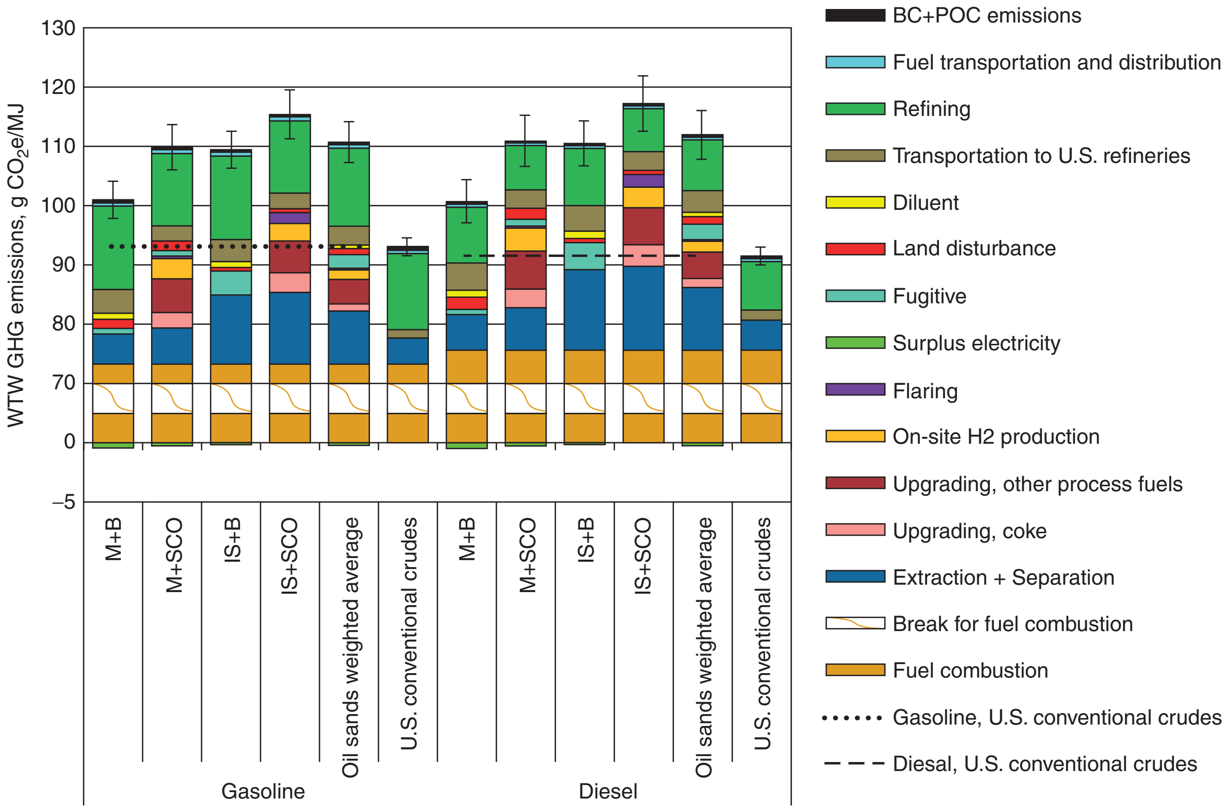

Figure 2 WTW GHG emissions of gasoline and diesel. Source: Cai et al. (2015). See reference for explanation of basis for vertical bars. (M, Mining; B, bitumen; SCO, synthetic crude oil; IS, in situ).

wheel: WTW)[6] of producing and using fuels derived from oil sand feedstocks from the four main extraction and processing methods described in the Annex (M: mining; B: bitumen; SCO: synthetic crude oil; IS: *in situ*). Overall estimates for WTW emissions are shown in Figure 2 for petrol and diesel from each of the four oil sand processing pathways. These are also compared with fuels sourced from US conventional crudes.

Figure 2 indicates that the WTW GHG emissions of oil-sands-derived petrol and diesel in the USA averaged 100–115 and 99–117 gCO_2eq/MJ, respectively, depending on the type of production technology used. Comparative figures for US conventional crudes were 92 and 91 gCO_2eq/MJ (petrol and diesel respectively). If petrol and diesel were produced with an energy-based weighted-average mix[7] of the four oil sands pathways, they would have 18% and 21% higher WTW GHG emissions than when sourced from conventional oils in the US.

Cai et al. (2015a) also compared their calculations with other studies, and the differences in the system boundaries between studies. These included studies sponsored by the Alberta Government (Jacobs Consultancy 2009, 2012) and show a degree of consistency between recent calculations from different sources. Most recently, Nimana et al. (2015) used a theoretical model to explore a range of scenarios for oil sands and calculated WTW GHG emissions from 106.8 to 116 gCO_2eq/MJ for petrol.

Comparing recent studies with the earlier expert advice received by the Commission (Brandt, 2011) requires some adjustment. Cai et al. (2015) used US conventional crudes as their comparator, so include transport from Alberta to US refineries in their calculations. Comparing these results with Brandt's 2011 study, requires inclusion of any emissions from transporting oil-sand-derived feedstock to EU refineries, and also to compare with EU conventional feedstock emissions rather than those in the USA. ICCT (2014a) estimate the emissions from tanker transport to the EU as 1.1 gCO_2eq/MJ. If we add this to Cai et al. (2015)'s figures, and also adjust for the difference between US and EU conventional feedstock emission baselines, then the ranges and averages for

[6] The 'Well to Wheel' life-cycle emissions of fuels are the total emissions associated with the extraction and processing of the feedstock, its delivery to the refinery gate, the emissions associated with refining to produce petrol or diesel and their delivery to the pump, and the emissions from combustion of the fuel in the vehicle's engine.
[7] As above, this adjusts for the relative amounts of oil-sands-based feedstock coming from each pathway.

Table 1 Comparing recent emission estimates with 2011 estimates derived for the EU (Brandt, 2011) (figures for petrol in gCO_2eq/MJ)

Oil sand fuels* plus tanker to EU	Ratio of oil sand fuels* to 2011 EU conventional baseline (87.1)	Ratio of oil sand fuels* to 2015 EU conventional baseline (93.2)
Range (average)	Range (average)	Range (average)
100.6–115.8 (109.6)	1.15–1.33 (1.26)	1.08–1.24 (1.18)

**Ranges and average emissions from Table 1 of Cai et al. (2015).*

WTW GHG emissions are shown in Table 1, where the results are also compared with the baseline figures used in Brandt (2011).

Comparing the latest estimates of GHG emissions from oil-sands-derived petrol with the current[8] EU baseline of 93.2 gCO_2eq/MJ, the average difference is 18%. However, if we use the same conventional oil baseline as Brandt in 2011 (87.1 gCO_2eq/MJ), this would be 26%. In any case, we may conclude that the results of the latest studies are in broad agreement with those of the earlier EU expert assessment (Brandt, 2011).

The recent studies have extended the system boundaries of life-cycle assessment calculations but some sources remain excluded. As pointed out by Cai et al. (2015), they do not include energy used to transport bitumen from a stand-alone mine to a stand-alone upgrader, nor the energy (and associated emissions) embodied in infrastructure build or in capital equipment such as wells, trucks, or upgraders. We can also note that no studies have attempted to consider the final land reclamation stage which would, at least for mining projects, probably involve similar emissions to the mining preparation stage.

3. GHG intensity of fuels from conventional and oil shale source

Since 2011, production from other sources of unconventional oil has increased– particularly oils extracted from oil shales in the USA. These have been less well-studied than oil sands, but some studies suggest that WTW life-cycle GHG emissions may be 20–75% higher than those from conventional liquid fuels, depending on the process used (Brandt 2008, 2009; Brandt et al., 2010). However, recent studies of two of the largest areas for oil shale production in the USA (Ghandi et al., 2015; Brandt et al., 2015) suggest that with better management and reduction of emissions from external processes such as flaring, GHG intensity can be brought down to levels similar to the average of conventional US sources.

More data have also become available on conventional sources showing that life cycle emissions from different sources of crude oil cover a wide range. Studies estimating emissions from crude oil both in the USA (Jacobs, 2009) and in the EU (Jacobs Consultancy, 2012; ICCT, 2014) show how GHG emissions depend on oil source and production methodology. In particular, sources which involve large amounts of flaring (e.g. Nigeria and Iraq) increase emissions significantly[9]. Recent studies on US crudes (Rahman et al., 2015) found one heavy oil (from California's Kern County) which, when used as a feedstock for petrol, was associated with WTW GHG emissions of 127.74 gCO_2eq/MJ.

Recently, Gordon et al. (2015) have introduced an 'oil-climate index' which can be used to compare the GHG intensity of different crude oils. This applies available models of the three main stages of the life cycle (upstream oil emissions from extraction and transport to the refinery; midstream emissions at the petroleum refinery; and downstream end use stages) to estimate GHG emission for each stage and over the whole life cycle (WTW). Initial calculations for 30 oil field sources (Figure 3a) show upstream GHG emissions to vary by a factor of 10 between the heaviest and lowest emitters. At the midstream (refinery) stage, a 7-fold difference was found (Figure 3b). When GHG emissions at the downstream (end-use) stage are added, there is an over 80% difference in total GHG emissions between the lowest and highest GHG-emitting oil feedstocks. These comparisons also show that the highest emissions were from 'conventional' crudes as well as from oil sands (shale oils were not included in this study), demonstrating that classification of feedstocks into categories such as 'conventional' or 'unconventional' does not necessarily relate to their GHG emissions intensity.

8 This change was made by the Commission owing to the somewhat broader range of values for conventional crude which had recently become available. See also Section 3.

9 For instance Jacobs Consultancy (2012) find a range of values for diesel fuel from 84 gCO_2e/MJ (light North Sea crude) to 99 gCO_2e/MJ (heavy Venezuelan crude).

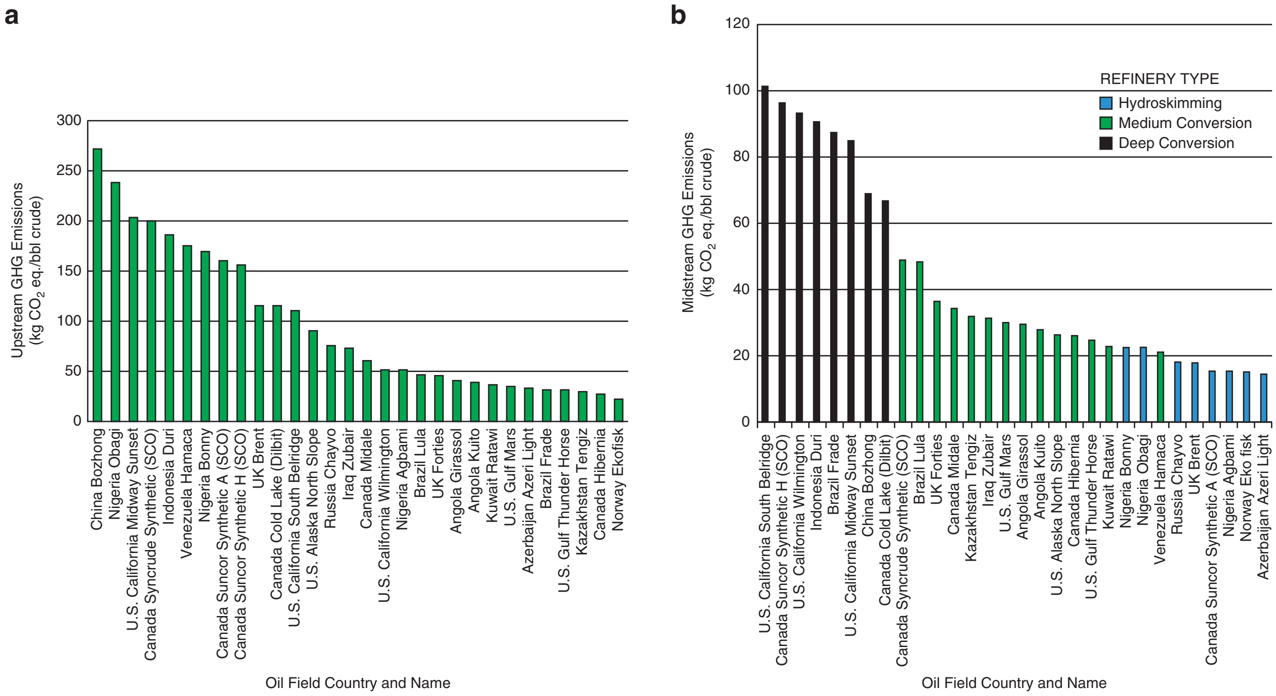

Figure 3 GHG emissions for 30 oils at upstream (oil production) (a) and midstream (refinery) (b) stages[10]: Gordon et al., 2015.

4 Policy implications

As a general observation, EASAC notes that since the conclusion of COP21, commitments to update pledges to incorporate further reductions in GHG emissions imply that the EU will need to continue to look for reductions in GHG emissions in all sectors including transport. The question of how to deal with fuels of different GHG intensity thus remains on the agenda, including how the climate impact of different sources of oil feedstocks can be factored into policymaking and market values of petroleum products. Against this background, EASAC makes the following comments relevant to the EU's consideration of future policy options.

EASAC notes that the original EU expert assessment (Brandt, 2011) appears basically sound in the light of the latest information. The average GHG emission of petrol based on oil-sands-derived feedstock was found in 2011 to be 107 gCO_2eq/MJ whilst the latest analyses estimate ~110 gCO_2eq/MJ (Table 1). The latest findings are consistent with other studies and indicate that switching from average conventional oil feedstocks to those derived from oil sands would increase the GHG emissions associated with EU consumption of transport fuels.

4.1 The GHG intensity of oil-sands-derived fuels

Recent oil sand life-cycle assessments contain improved calculations of land use change, venting and other factors, but some emissions remain excluded from even the latest assessments;

- *Infrastructure and heavy equipment:* (although emissions embodied in these are typically small because of the long lifetime of the equipment over which emissions can be averaged).
- *Land reclamation:* for current oil sands projects (in Alberta), this is mandatory, so that there will also be GHG emissions associated with this stage. For reclamation of mining projects, this may involve shifting soil, contouring, etc. involving similar amounts of material to the initial overburden removal[11].
- *Tailings:* these emit volatile organic compounds, carbon dioxide and methane but there are limited data on this (Small et al., 2015).
- *Land use change:* some assumptions in calculations of these impacts may be overly optimistic (Yeh et al. (2014) assume 50 years of foregone sequestration

[10] Converting the units used by Gordon et al. (2015) to those used in this paper; 1kgCO_2eq/bbl crude = 5.86gCO_2eq/MJ.
[11] In Cai et al. (2015), these emissions are included in the ~6 gCO_2eq/MJ assigned to the mining and separation stage.

before full forest recovery, which may be on the conservative side for mining projects).

- *Changes in the ecosystem:* changes from boreal to upland forest and associated impacts on natural capital and ecosystem services (see Annex) have not been assessed and valued.

The factors listed above should be included in any future life-cycle assessments required by the EU.

4.2 The GHG intensities of other fuels

Recent surveys show that there is a wide range of GHG emissions between different sources within the same category of feedstock (both 'conventional' and 'unconventional'). This makes the selection of 'default' values for each category (as listed in the 2015 Directive on calculation methods but not used to meet the requirements of the Fuel Quality Directive) particularly difficult. As already mentioned, the EU does not currently propose to use default values for its future regulations in this field.

4.3 Related policy issues

From the perspective of reducing GHG emissions, it is important to put in place market signals which influence investment decisions and drive innovation towards lower carbon fuels. Currently, oil feedstocks with very different contributions to climate change forcing are failing to have this aspect factored sufficiently into production and purchasing decisions.

From a scientific perspective, factors that should be considered in future policy[12] include the following:

- Differentiating between feedstocks of different GHG intensity is appropriate if global emissions from the EU transport sector are to be properly accounted for, and for EU purchase decisions to deliver market signals to influence investment decisions and innovation priorities.

- While the allocation of responsibility for accounting for emissions between oil users and producers remains a political question, transparency of reporting on the GHG emissions of different sources of oils is still important for decision-making.

- The EU's upstream emissions reduction (UER) scheme is expected to encourage reductions in emissions from venting and flaring. However, many GHG emissions come from gassy oils, heavy oils, watery and depleted oils, as well as oil sands and oil-shale-derived crude oil, where high emissions are due to the energy intensity of the extraction process and other factors. The UER scheme or other measures should encourage those who are responsible for future investment decisions to sufficiently take into account the GHG intensity of the fuels which are to be produced by the projects.

- A major limitation when applying climate-based policy measures to transport fuels remains the lack of reliable information, since operators in many regions of the world are subject to few formal data publication requirements.

[12] A global carbon market with an appropriate carbon price uniformly applied would provide appropriate market signals. Carbon pricing is applied in some countries (including the EU Emissions Trading System) and governments in Canada and Alberta plan to introduce a carbon tax. Nevertheless, such taxes are not applied globally and considerable uncertainty remains over the carbon price required to achieve a given global warming target. Regulatory measures thus remain a policy option.

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Annex Measuring the greenhouse gas intensity of oil sands feedstocks

To determine the GHG emissions related to fuel production and use from oil sands, detailed calculations are required on emissions from each of the steps that must be taken to extract and process the bitumen, and then to refine it to produce the end fuel for use in transport (whether petrol or diesel). In practice, each oil sands project is distinct because of the differing characteristics of oil sands reservoirs, recovery technologies, and operational choices. While some cold production or chemical diluent processes are applied on a small scale, most large-scale production falls into four categories:

(1) Mining to produce bitumen for refining (M+B) (seldom used in current practice).
(2) Mining bitumen for upgrading to synthetic crude oil (M+SCO).
(3) *In situ* extraction to produce bitumen for refining (IS+B).
(4) *In situ* extraction to produce synthetic crude oil (IS+SCO).

While initial oil sands processes involved mining, only a limited number produce bitumen (a) and most mined bitumen is upgraded to SCO. Moreover, the bulk of the established reserves are below the depth accessible from mining and thus *in situ* technology is likely to dominate in the future. Key sources of GHG emissions are summarised in Table A1.

With mining (Table A1), forest is removed and commercially valued timber harvested, and the soil over the bitumen deposits (overburden) removed by shovels and transported by trucks to storage areas. The removal of the biomass increases emissions from loss of the CO_2 absorptive role of the vegetation destroyed, release of carbon in the soil when exposed to air (especially significant with peaty soils) and other mechanisms related to land use change[13]. The land areas affected include mine sites, overburden storage, tailing ponds and end pit lakes. The mined bitumen-containing material is transported to central crushing and slurry facilities and piped to extraction centers. Some mining and processing equipment is powered with electricity co-produced on site from natural gas, upgrading process gas, or by some of the large quantities of coke produced in the SCO upgrading process.

Deeper deposits are accessed through *in situ* technologies that include injecting steam underground to enable extraction of the bitumen. *In situ* extraction requires equipment and energy to drill the boreholes to inject steam and return the bitumen and water mixtures. Land areas are affected by infrastructure such as central processing facilities, networks of seismic lines, access roads, pipelines, and well pads. In terms of the area of land disturbed per volume of bitumen produced, *in situ* projects have around three times higher land disturbance than mining projects (Yeh et al., 2014, 2015).

Table A1 Production of bitumen from oil sands stages and sources of GHG emissions

Stage	Activity	Source of GHG emissions	Relevant to:
Mining preparation	Forest cover clearance, removal of top soil and overburden	Manufacture of equipment, fuel production and use, land use change emissions	M+B, M+SCO
Mining	Digging up the oil sand deposits and transfer to processing site	Manufacture of equipment, fuel production and use	M+B, M+SCO
In situ extraction	Drilling boreholes, heating and injecting hot water, pumping and separators	Manufacture of drilling equipment and support, energy for heating and pumping	IS+B, IS+SCO
Extraction and processing	Mixed with steam/hot water, screened and separated into bitumen and tailings	Energy to heat water and generate steam, manufacture and operate process equipment, transport tailings, venting and flaring	All
Raw SCO upgrading	Contaminant removal and reducing viscosity	Energy and raw materials (e.g. diluting hydrocarbons, coke, hydrogen)	M+SCO, IS+SCO
Waste	Constructing and managing tailings ponds	Manufacture of equipment, fuel production and use, fugitive emissions	All
Remediation	End-of use regeneration of top soil and vegetation	Manufacture of equipment, fuel production and use	All but especially M+B, M+SCO

M: mining; B: bitumen; SCO: synthetic crude oil; IS: *in situ*.

[13] Studies on life-cycle emissions for the EU Fuel Quality Directive consider only GHG emissions and do not attempt to evaluate ecosystem destruction and biodiversity loss associated with forest removal (or other potential pollutant risks such as water pollution). These remain a matter for the national government to address in conformity with other treaty (e.g. Biodiversity Convention) obligations and are outside the scope of this study.

At the extraction facilities, bitumen froth is separated from sand, requiring hot water and consuming much of the energy used. In integrated operations, by-products such as gas and coke produced elsewhere in the upgrading process can provide some of the necessary heat and power. After this primary separation stage, the bitumen froth is treated to remove water and solids, using naphtha or paraffinic solvents as diluents. This produces bitumen ready for either dilution prior to sale or for upgrading to SCO[14]. Upgrading to SCO is achieved by high-temperature refining and injection of hydrogen which requires additional energy and fuel.

Regarding waste, studies generally report that each volume of mined oil sands requires three times that volume of water, and produces on average of four to five times that volume of tailings (Yeh et al., 2014). This is transported to large tailings ponds[15], where organic compounds accumulate from residues of diluent solvent and bitumen giving rise to emissions of volatile organic compounds, reduced sulfur compounds, carbon dioxide, and methane (Small et al., 2015). Fugitive emissions of methane and CO_2 also come from venting and flaring at each stage of the process.

Finally, in the case of oil sands from Alberta (Canada), local law requires that all lands disturbed by oil sands operations should be reclaimed. To do this, operators use leftover sand, consolidated tailings and overburden to fill in the mine pits, contour the landscape to allow for surface water movement and drainage, and then cover with topsoil and replant with indigenous vegetation. Remediation of tailings ponds (pits that contain a mixture of water, clay, sand and residual bitumen) is also required but an environmentally-effective methodology has yet to be demonstrated. *In situ* projects reclaim disturbed areas as various stages are completed (e.g. after seismic surveys are complete, those areas cleared can be revegetated ahead of the main project facilities).

Yeh et al. (2014) estimate that, for the entire lifetime of current major projects, the total land use disturbance will result in a total of 1226 km^2 requiring reclamation. Limited reclamation has been completed in some pilot projects[16], and involved large scale earth-moving equipment with its associated emissions. Debate continues on the definition and adequacy of reclamation. Original boreal forest and peatlands will be replaced by upland forest and tailings storage lakes, which Rooney et al. (2012) estimate will release 11.4 million to 47.3 million tonnes of stored carbon from the landscape from changes caused by currently approved mines, and reduce carbon sequestration potential by 5,734–7,241 tonnes of carbon per year. However, a more recent publication by Yeh et al. (2015) suggests that these are underestimates, and 107 million to 182 million tonnes will be released owing to the removal of 500–2,400 km^2 of boreal forest, including peatlands.

14 Raw bitumen will not reliably flow through a pipeline at ambient temperatures and must be diluted with a lighter hydrocarbon before transport. If delivered directly to a refinery, such bitumens would require more intensive refining, owing to their high carbon to hydrogen ratio, and their sulphur and metals content. These quality deficiencies would also lead to a less valuable range of petroleum products. In many cases therefore, the bitumen is upgraded at the site to produce synthetic crude oil before transport to the oil refinery.

15 There are currently about 77 km^2 of oil sands tailings ponds water in Alberta. http://oilsands.alberta.ca/tailings.html

16 In March 2008, Syncrude's Gateway Hill was certified by the Government of Alberta as fully reclaimed. However, the area reclaimed is just 0.15% of the area currently affected by oil sands development and it may be impossible to restore the original complex wetland ecosystems of the original boreal forest (see Yale University; http://e360.yale.edu/feature/on_ravaged_tar_sands_lands_big_challenges_for_reclamation/2751/).

EASAC

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