

Supplementary Information Matters Arising Response

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Methods

Emission reductions from subsidy removal versus 1.5°C and 2°C pathways

We compare our estimates of emission reductions from subsidy removal to those observed in 1.5°C and 2°C pathways, by selecting all pathways which are 1.5°C or 2°C compatible for the four models from our original study in the IPCC database and where respective no-policy Baseline could be identified^{1,2}. We then calculated the emission reductions from the 1.5°C and 2°C pathways for each model through 2030 compared to the respective no-policy baseline. For the emission reductions from the removal of higher production subsidies, we used results from the WITCH model to calculate the emission reductions from the higher production subsidy sensitivity run and compared it to WITCH's 1.5°C and 2.5°C pathways^{1,2}.

Modelling accelerated depreciation and oil extraction economics

To analyse the effect of accelerated depreciation schemes, we created a discounted cash flow model for an oil extraction project. We use a stylized representation of oil production that assumes production starts at a maximum and follows a declining pattern of 6% per year³ and each oil field has a 20 year lifetime. We chose 20 years because oil fields generally last between 15 to 30 years⁴, however deep water fields generally operate for less than 10 years and tight-oil for less than five. Additionally, while a full oil field may last for longer, this generally involves drilling new wells (and incurring new capital expenses and tax deductions). We tested the robustness of our results against a 30-year lifetime which would change our estimate for the effective global subsidy rate by less than \$0.1/barrel.

We use our model to calculate the difference in the breakeven price of a project under normal and accelerated depreciation rules. In the normal depreciation case, the capital expenses are reduced according to national depreciation rules that allow projects to recover all or part of their capital expenditure by deducting them from their taxes^{5,6}. In the accelerated depreciation case, we model the accelerated depreciation scheme available to the oil industry⁷ (Methods Table 2). We express how the accelerated depreciation scheme affects the hypothetical cash flow of investors as the effective subsidy rate. The effective subsidy rate is a function of five main parameters: discount rates^{8–12}, the ratio of capital to operating expenses¹³, the breakeven price^{14–16}, the corporate tax rate^{17,18}, and the standard and accelerated depreciation arrangements^{5–7,16}.

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Discount rates in the oil sector

With respect to discount rates, empirical estimates of investor discount rates in the oil sector depend on the method used and range between 9-16% if obtained by surveys of companies⁸, 11-22% by surveying institutional investors¹⁹, 12-17% on a pre-tax basis⁸ and 6-16% on a post-tax basis^{9,11} obtained by calculating the weighted average cost of capital (WACC) and adding a sectoral risk premium of 0-2 points⁹, 7-21% when examining the yield rate of individual securities¹² and 16-19% on a pre-tax basis through surveying property-specific risks⁸.

For measuring the effect of accelerated depreciation on investor cash flow, we need post-tax discount rates, because accelerated depreciation schemes only affect the post-tax cash-flow. Post-tax discount rates are generally a couple of percentage points below the pre-tax discount rates^{9,11}. This is why we don't see Iyer et al.¹⁰ who report pre-tax discount rates for the electricity sector as a useful analogue for post-tax oil production discount rates which Erickson et al. cite as a source for higher discount rates.

When translating these company-specific ranges to the full oil economy, it is also useful to note that discount rates (above 12% post-tax) are generally only observed for small independent producers⁹, specific properties⁸ or very risky securities¹². This is because the bigger the company, the more aggregate the risk pool, and the lower the discount rate. To have discount rates in the full oil sector of 20%, we would need to observe rates for some investments significantly over 20% (not just the riskiest at 20%). Indeed, the WACC for some 300 publicly-traded production and exploration firms (both large and small) between 2014-2019 has only varied between 7-9%¹¹ which would translate to a 9-11% discount rate. (Note for ref. ¹¹ we used the internet wayback machine to access 2014-2018 data). The second source which Erickson et al. cite for 20% discount rates in the oil industry reports an 8% yield rate across the full sector and 13% yield rate across speculative grade investments¹².

This is why we see rates above 15% for the full oil economy as highly speculative and use 10% for our central case. Nevertheless, we test how our results would change under discount rates of 7.5% (since Rystad Energy's oil cost curve which both of our and Erickson et al.'s analyses use is based on a 7.5% real discount rate¹⁴), 15% and 20% and find they are consistent with our general findings (Methods Table 1).

Methods Table 1. Our analysis of accelerated depreciation schemes under different discount rates. For the USA, all 2016 analysis is presented in italics including Erickson et al.'s estimate for USA IDC scheme for comparison. "CA" refers to Canada and is the "CAJAZ" region whose oil production is dominated by Canada (over 98%). "NO" refers to Norway, "RU" to Russia, "SA" to Saudi Arabia and "NG" to Nigeria.

Discounted cash flow model of accelerated depreciation schemes under different discount rates from those presented in the main table					
7.5%		15%		20%	
Our analysis of accelerated depreciation schemes - main table column [C]		Our analysis of accelerated depreciation schemes - main table column [C]	Erickson et al. USA 2016 case main table column [D]	Our analysis of accelerated depreciation schemes - main table column [C]	Erickson et al. USA 2016 case main table column [D]
Effective production subsidy rate (\$/barrel)					
USA	4.0 (2016 case) 1.5 (2019 case)	6.2 (2016 case) 2.4 (2019 case)	5.8	7.0 (2016 case) 2.8 (2019 case)	7.3
Other Regions	CA: 0.4 – 1.2 [0.8] NO: 0.8 – 1.9 [1.4] RU: 0.8 – 1.7 [1.4] SA and NG: 0	CA: 0.5 – 1.4 [0.9] NO: 0.9 – 2.1 [1.5] RU 1.1 – 2.4 [1.9] SA and NG: 0		CA: 0.7 – 2.0 [1.3] NO: 0.9 – 2.0 [1.5] RU 1.1 – 2.0 [2.5] SA and NG: 0	
Global	0.3 – 1.5 [0.8]	0.4 – 2.4 [1.2]		0.4 – 2.7 [1.4]	
Change in global oil extraction/consumption, mln barrels/year due to global effective subsidy rate range (low oil price scenario and using Erickson et al. elasticities)					
	30 – 160 [90]	40 – 250 [130]	620	40 – 290 [150]	770

Modelling the national accelerated depreciation schemes

We start by comparing the results of our model using the 2016 assumptions for the USA to Erickson et al.'s estimate of the impact of the IDC subsidy on the 800 USA oil fields which also uses 2016 assumptions. We find that our model is well calibrated to Erickson et al.'s results for the USA 2016 case. The exact match of course cannot be achieved because we don't use exact data on all USA oil fields, which lead us to overestimate field lifetime due to the prevalence of tight oil fields captured in Erickson et al.'s more detailed analysis. Another reason our results are higher is because our model uses real values while Erickson's analysis uses nominal. All this means that if anything, our model overestimates the effective subsidy rate.

We use our model to explore the effects of various assumptions on the impact of accelerated depreciation subsidy on producers' costs and thereby to extrapolate Erickson et al. et al.'s estimate of the effect of the IDC subsidy on 800 USA fields in 2016 to the USA in 2019 and the world as a whole.

This enables us to explore how capital expenses, national tax rates and the accelerated depreciation scheme design affect the effective subsidy rate in three national cases which are well documented: Canada, Norway and Russia.

Methods Table 2. Modeling protocol and parameters for our five cases of accelerated depreciation schemes. For capital to operating cost ratios we digitized Rystad data cited in the *Wall Street Journal*¹³.

	Corporate tax rate	Break-even price reference and resource group	Accelerated and standard depreciation scheme modelling
USA 2016 case	35% ¹⁷	NA tight oil ¹⁵ (We use this for 2016 because it is closer to what we estimate from Fig. 3 of Erickson et al. ¹⁶ for the breakeven price in 2016.)	<ul style="list-style-type: none"> - Under the IDC, integrated producers are allowed to deduct 70% of capital expenditures in the first year and the remaining 30% over five years and independent producers are able to deduct 100% in the first year. - We follow Erickson et al.'s¹⁶ assumptions for modelling the IDC so assign 85% of capital expenditures to intangible (rather than fixed asset) costs which are then tax deductible. - We calculate the standard depreciation using the cost depletion method whereby the capital costs are deducted over time in proportion to production^{16,20}. - We assume two-thirds of American oil is produced by independent producers²¹.
USA 2019 case	21% ¹⁷	Mean of NA tight liquids and Shelf ¹⁴	<i>same modelling approach</i>
Canada	15% ¹⁸	Full range between NA tight liquids and Oil sands ¹⁴	<ul style="list-style-type: none"> - Exploration expenses can be deducted in the year they're incurred and development expenses at 30% on a declining basis⁷. - The standard depreciation rate for oil and gas is 16.7%⁵. - We assign 20% of capital costs to exploration based on estimates that 17-19% are for exploration^{22,23}.
Norway	22% ¹⁸	Shelf range ¹⁴	<ul style="list-style-type: none"> - The depreciation rate for capital expenses in oil and gas is 14-16.7% and depreciation rates in other sectors range from 0-30%⁶. - We model 16.7% (straight-line) for the accelerated case and a 14% declining balance for the standard case which is the rate for rigs⁶.
Russia	20% ¹⁸	Russia onshore range ¹⁴	<ul style="list-style-type: none"> - Oil and gas capital expenditures are deducted at three times the standard rate applied to the sector which is the total value divided by the lifetime of the asset^{6,7}. - We model 15% for the accelerated case and 5% for the standard case.

We should note that the oil sectors in both Norway and Russia are partially state owned and taxed at a much higher rate than the rest of the economy – reaching over 70% on profits (in Russia this is still in a pilot phase in several regions)^{24,25}. This makes defining and measuring producer subsidies conceptually and empirically challenging. For our calculation we follow a similar approach that we do with the USA and Canada and explore the difference between a hypothetical case when the oil industry would be taxed similarly to the rest of the economy (no-subsidy case) and when it would be only given an accelerated depreciation scheme, but not a higher tax rate (subsidy case). The results of this calculation show that the USA has the strongest accelerated depreciation scheme among our cases (Methods Table 3).

Methods Table 3. Effect of accelerated depreciation schemes of our five cases (and Erickson et al.'s result for comparison) expressed in percent change in breakeven price

		Percent change of breakeven price				
	Discount rate	7.5%	10%	15%	20%	
US-2016 (presented in Erickson et al. MA)			6.0%	8.2%	10.4%	
US-2016 (our calculations)			6.2%	7.6%	10.8%	
US-2019			3.2%	4.0%	5.1%	5.9%
Canada			1.2%	1.4%	1.8%	2.0%
Norway			2.8%	3.0%	3.1%	3.0%
Russia			2.4%	2.8%	3.3%	3.4%

We also did an exploratory analysis to identify the presence and characteristics of accelerated depreciation schemes for other oil producers. In Saudi Arabia and Nigeria, two OPEC countries, the depreciation rates for the oil industry are 20%⁶ which is lower than for other sectors. In Saudi Arabia factories and non-oil industrial plants have a 25% depreciation rate and in Nigeria machinery is depreciated at 50%, agricultural and mining equipment at 95%⁶. We find no other evidence for accelerated depreciation in OPEC or Middle Eastern countries.

Calculating a global effective subsidy rate

To estimate what effect accelerated depreciation schemes have on global oil production, we express the effect of accelerated depreciation schemes as a percentage of breakeven price (Methods Table 3) and calculate the weighted (by volume of resources) average of the change in breakeven price across eight major groups of oil reserves from Rystad energy using high, median and low estimates for breakeven price which span a 60% confidence interval in each oil reserve group¹⁴.

For each group of reserves, we assign a low and high subsidy effect (Methods Table 4, the USA 2019 case is from our own calculations see Methods Table 2). For the central estimate, we calculate the mean change in breakeven price between the low and high case.

Methods Table 4. Mapping reserves to our effective subsidy estimates to estimate the global effective subsidy rate from accelerated depreciation schemes. For the reserves and break-even prices, we digitized data from Rystad energy¹⁴.

Resource group	Low estimate	High estimate
Onshore Middle East	None	None
NA Tight Liquids	Canada	USA (2019 case)
Shelf	None	USA (2019 case)
Deepwater	None	USA (2019 case)
Russia onshore	Russia	Russia
Extra heavy oil	Canada	USA (2019 case)
Row onshore	Canada	USA (2019 case)
Oil sands	Canada	Canada

We subsequently calculate the weighted average change of breakeven price for a low, high and central estimate globally based on the distribution of resource groups in the Rystad supply

curve¹⁴. For the low and high estimates, we calculate the low and high breakeven prices respectively (60% confidence range) from the Rystad supply curve¹⁴ multiplied by the low and high case estimates of subsidy for each resource group. For the **central effective subsidy rate**, we multiply the mean change in breakeven price for each resource group by the median breakeven price of each resource group.

Variation in the effect of producers' costs on global oil consumption

To calculate the change in global oil consumption arising from the change in producer's cost we use the same simple oil model as Erickson et al. with a range of previously reported elasticities and assuming the same global oil consumption of 37,000 million barrels/year. Erickson et al. report their results for each oil price using a single supply and a single demand elasticity. They rely on measuring the slope between different polygons in the Rystad cost curve of global liquids in 2030 to calculate the supply elasticity, however, there is huge uncertainty of the breakeven price for different asset classes even in the supply curve they use¹⁴. Just since 2016, the median breakeven price of the North American tight oil has fallen 30%. This uncertainty makes sense given that supply elasticity is influenced by technological development and the strategic behaviour of key oil suppliers such as OPEC^{3,26,27}. Additionally, the literature on long-term demand elasticity finds that it can vary between -0.01 to -1.81²⁸⁻³⁰. To test the effect of supply and demand elasticity uncertainty on the effective subsidy rate in the simple oil market model, we use a range of elasticities from Erickson and his co-authors' earlier work where they first introduced³¹ ($\epsilon_s = 0.1$ to 0.6 and $\epsilon_d = -0.054$ to -0.36) and applied¹⁶ ($\epsilon_s = 0.87$ and $\epsilon_d = -0.2$) the simple oil market model.

Estimating the emission impact of accelerated depreciation schemes

To estimate the additional emissions reductions from accelerated depreciation schemes, we report the increased emissions between the main subsidy and high production subsidy case from our original article. This is a good comparison with Erickson et al.'s discussion of accelerated depreciation schemes because the subsidy rates are on the higher end at the global level and higher in most regions of what accounting for accelerated depreciation schemes with a cash flow basis would yield. In our original study this effect was 590 mln barrel/year if producer subsidies were increased 10-fold from the main case (15-fold for oil).

These figures are not directly comparable to Erickson et al.'s simple oil market model because the latter presume an instantaneous removal of the scheme in 2019 with immediate investor reaction that directly propagates to oil extraction and consumption in 2030. Our original analysis modelled a more realistic subsidy removal scenario between 2020 and 2030 triggering a gradual response of investors constrained by systemic and dynamic feedbacks such as long-term capital dynamics, fuel-switching, and general equilibrium price effects.

We also compare this higher production subsidy scenario to the subsidy removal scenario within the same model and not to the full suite of models. The 10-fold increase in the size of production subsidies in the sensitivity run of our original study increases the emission reductions from subsidy removal by 0.3 GtCO₂/year in 2030 or about 13% higher than that model's main subsidy removal scenario. This uncertainty is far smaller than the 1.7 GtCO₂ range resulting from the differences in our five models capturing different elasticities and solution mechanisms and the 0.6 GtCO₂ range resulting from different baseline assumptions on socio-economic and technological futures. Comparing the effect of a given uncertainty within a single model is the standard way to capture the effect of a given uncertainty.

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