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DISCUSSION BRIEF

Carbon lock-in from fossil fuel supply infrastructure

Introduction

A transition to a low-carbon economy is essential to ensuring a safer climate, but it will not be easy. Despite the well-documented benefits of decarbonizing energy systems,[1] the declining costs of renewable energy and high-efficiency technologies, and the promise of further innovations, the world continues to rely heavily on an abundant and growing supply of fossil fuels.[2]

This discussion brief focuses on a key concern with ongoing investments in fossil fuel supply and the technologies that use these fuels: "carbon lock-in".[3] The essence of carbon lock-in is that, once certain carbon-intensive investments are made, and development pathways are chosen, fossil fuel dependence and associated carbon emissions can become "locked in", making it more difficult to move to lower-carbon pathways and thus reduce climate risks.

For example, near-term investments in coal-fired power plants, with their low operating costs, long technical life-spans, and strong institutional and political support, increase the future costs of achieving a given emissions target.[4] So, too, might natural gas power plants, fossil-fuelled vehicles, and inefficient buildings and heating technologies.[5] Overall, the International Energy Agency (IEA) has found, if energy investments favour high-carbon technologies through 2020 instead of low-carbon alternatives, the medium-term investment (through 2035) needed to reach low-carbon objectives would increase fourfold.[6]

Here we propose a two-step approach to gauging the relative lock-in risks of investments in fossil fuel exploration and extraction:

- First, we identify investments in fossil fuel resources and infrastructure that are likely to be inconsistent with climate protection objectives, as reflected in a metric of "over-produced" fossil fuels that captures the *scale* of lock-in effects.
- Second, we evaluate the *strength* of this lock-in – i.e. the extent that, once such investments are made, they may be difficult to move away from, or "unlock" in the future. We assess the strength of lock-in by two metrics: the relative amount of capital invested in these over-produced resources, and the relative amount of economic "rents", or profits, likely to accrue from them.

Together, these analytical steps and metrics can help policy-makers identify the fossil fuel deposits for which new investments are most likely to lead to carbon lock-in. Below we apply this approach at the global scale, to illustrate the methodology and to provide general insights on the broad categories of resources that may pose the greatest lock-in risk. With sufficient data and scenarios, this approach can be applied at various geographic scales. We also discuss equity issues that might arise in using the results to plan for a low-carbon future.

While this approach can be applied to any time frame, we focus here on the year 2030, which is the target year of current negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). Moreover, fossil fuel production capacity and costs in 2030 will be heavily influenced by the choices made by policy-makers within the next few years, and the investments they encourage or deter.

Policy-makers are already showing a growing interest in the greenhouse gas emissions implications of fossil fuel supply,[7] and a small but growing body of research suggests that efforts to limit fossil fuel extraction could complement and increase the effectiveness of demand-side approaches to climate policy.[8] Research such as ours can inform efforts to integrate supply- and demand-side approaches.

An open-cut coal mine in the Upper Hunter Valley, New South Wales, Australia. Most of the coal produced here is exported to Asia.

Step 1: Assessing the scale of fossil fuel (carbon) over-production

Policy-makers (and investors) may have many reasons for assessing carbon lock-in risks associated with fossil fuel supply. They may want to ensure that their economies are competitive in a low-carbon future.[9] They may wish to limit the risk that low fuel prices or climate policies require the premature retirement of investments – i.e. "stranded assets".[10] They may also be concerned about "carbon entanglement", the process by which governments become so dependent on rents from fossil fuel production that they resist efforts to limit it.[11] Or they may simply want to understand how fossil fuel supply infrastructure decisions might affect their ability to achieve climate protection goals.

Whatever its motivation, such an assessment must be grounded in an understanding of fossil fuel resources[12] and future plans for their development. Accordingly, the first step of our approach is to assess existing and planned fossil fuel supply under both business-as-usual (BAU) and low-carbon scenarios. Comparing the two scenarios provides an estimate of fossil fuel **over-production** – production that appears to be inconsistent with a low-carbon pathway.

Investments associated with this over-production could be at risk of stranding if climate policies or low prices reduce demand for fossil fuels. Or over-investment could lead to carbon lock-in instead, if the investments deter climate action, making it likelier that fuel production and, by extension, consumption will continue at levels incompatible with a low-carbon pathway. In other words, capital investment in resources not needed under a low-carbon pathway not only creates the risk of asset stranding under future, more ambitious climate policies, but it may put that very ambition at risk.

The concept of over-produced fossil fuel resources (or carbon) is related to the notion of *unburnable carbon:* both refer to resources that would not be extracted under a low-carbon pathway. The key difference is that unburnable carbon typically reflects *all* resources and/or reserves that must be left in the ground,[13] whereas over-produced carbon reflects only the resources that would likely be extracted and consumed in a BAU scenario, but not in the low-carbon one.

To assess fossil fuel over-production, we rely on two scenarios in the IEA's *World Energy Outlook 2014:* New Policies, a BAU scenario that reflects countries' stated climate ambitions, including broad policy commitments and plans that have yet to be implemented, and the 450 Scenario; they correspond roughly to a 4°C and a 2°C warming path, respectively.[14] For simplicity, we consider only steam coal production and markets. Demand for coking coal does not vary significantly from BAU levels in many low-carbon scenarios, so it is unclear whether coking coal investments involve significant lock-in risks.

Under BAU in 2030, fossil fuel producers extract 5.0 billion tonnes of steam coal equivalent (tce), 37.0 billion barrels of oil supply (101.3 million barrels per day, or bpd), and 4.6 trillion cubic metres of gas. This level of production corresponds to, once combusted, 13 billion tonnes (Gt) CO_2 from steam coal, 14 Gt CO_2 from oil, and 9 Gt CO_2 from gas, after correcting for fuels not expected to be combusted, e.g. due to use as industrial feedstocks. In comparison, resource production in the low-carbon scenario is 65%, 85%, and 90% of BAU levels for steam coal, oil, and gas, respectively. Over-production in the BAU scenario is therefore 4 Gt CO_2 for steam coal, 2 Gt CO_2 for oil, and 1 Gt CO_2 for gas.

These estimates of over-production reflect the relative *scale* of carbon lock-in by fuel type, and thus the extent to which extraction, and corresponding upfront investment, might need to be scaled back to achieve a given climate protection objective. Unsurprisingly, coal is the fossil fuel on a path to be most over-produced, but the levels of over-produced oil and gas are significant as well. Understanding which types of coal, oil, and gas deposits are likeliest to be resistant to climate policy and prone to carbon lock-in requires further economic analysis. This is the second step of our approach.

Step 2: Assessing the strength of carbon lock-in

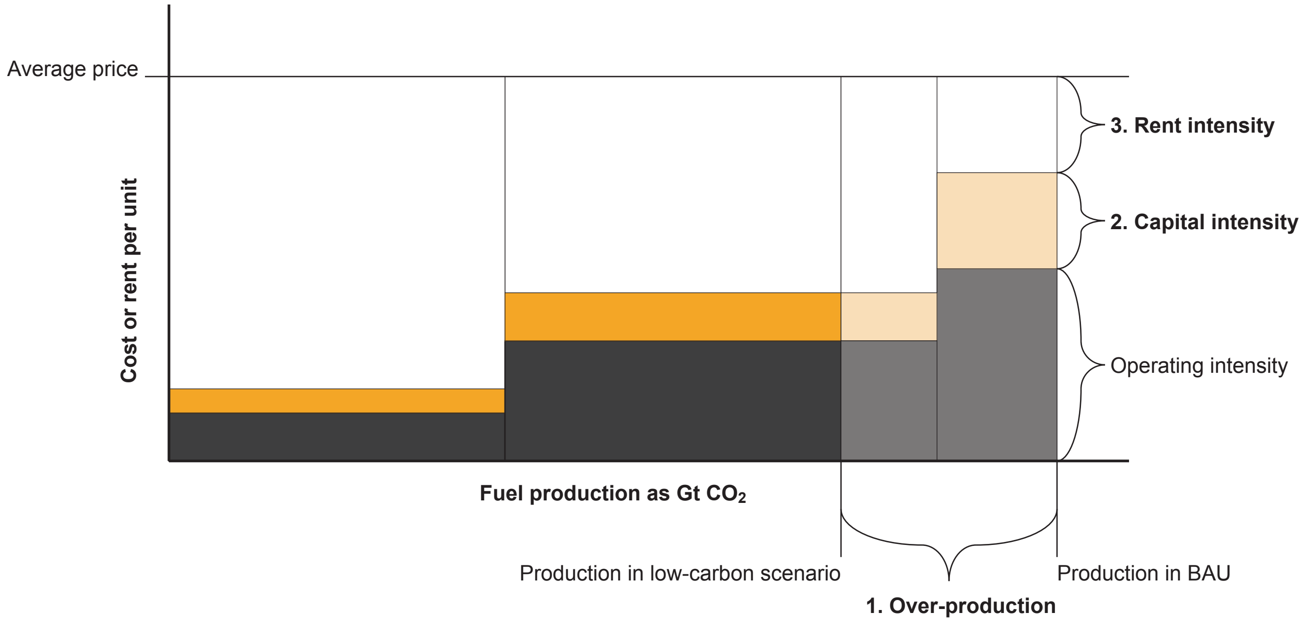
Now we look to the economics of different resources, focusing on two metrics – capital intensity and rent intensity – to illuminate which types of investments would be most difficult to "unlock" – or least likely to be stranded due to changing economics or climate policy.

Capital intensity (\$/t CO_2) represents the level of capital investment required to extract a given unit of a particular resource – for example, the cost of building an oil platform relative to the amount of oil to be extracted. Once these investments are in place, the marginal cost of production drops to the operating costs (plus any ongoing capital cost). Thus, in our example, even if the cost of the platform brought the total cost of the oil to 50 USD per barrel, if operating costs are only 20 USD per barrel, a rational investor might continue to produce even if the price of oil dropped below 50 USD. The more capital-intensive an investment, the more it may be insulated from price fluctuations once operational. In fact, all else being equal, operators may be likelier to continue operations of more capital-intensive resources, perhaps even after it stops being economically rational.[15] As a result, we suggest that the greater the capital intensity of a fossil fuel resource, the likelier it is that, once established, it will be extracted, even under unfavourable economic conditions.

We assess capital intensity as costs (in 2015 USD) for equipment and infrastructure for exploration, development (e.g. facility and well expenses), and maintenance and modification of resources to each market. For oil and gas, we use data from Rystad Energy;[16] for coal, we use Leaton et al. (2014)'s assessment of Wood Mackenzie data.[17] Both Rystad Energy and Wood Mackenzie are also used by the IEA in its *World Energy Outlook*, so the cost data used here are likely to be relatively consistent with the assumptions underlying the BAU and low-carbon IEA scenarios used here.

Rent intensity (\$/t CO_2) reflects how profitable each unit of a resource is likely to be. It is thus a key indicator of the economic incentive that owners have to keep producing, once capital has been invested. Here we express the metric as total rent (revenue minus production cost) divided by the carbon content of the fuel (i.e. CO_2 emitted upon combustion). From this we can extrapolate the carbon price at which further production of a resource might be rendered uneconomic. This metric is also a good indicator of carbon "entanglement" risks: how much money a government that relies on fossil fuel rents might stand to lose if it pursues policies

Figure 1. Illustrative schematic of fossil fuel production cost curves



to limit fossil fuel production.[18] Furthermore, economic rents can serve as a proxy for the relative political power of private-sector entities that benefit from production of a given resource.[19]

We estimate average rent intensities for oil and gas resources as the difference between total production costs and weighted-average global prices in 2030 of 104 USD per barrel of oil and 8 USD per million Btu (MBtu) of gas.[20] Coal prices in domestic markets can vary substantially, though they are generally lower than seaborne, or import, prices. Therefore we make a simplifying assumption that domestic prices for coal average about 70 USD per tonne, and import prices average about 85 USD per tonne, based on a review of IEA and Leaton et al. (2014)'s assessment of Wood Mackenzie.[21] Again, as local market prices vary, especially for coal and natural gas, actual rents may vary considerably from the averages estimated here.

Results: visualizing over-production and resource lock-in

We present the results of our analysis in three figures: one each for coal, oil and gas. All use a cost curve of production by category of resource in 2030 to illustrate three metrics:

- **Over-produced resources:** the resources in lighter shading (toward the right of each curve) that would be produced under business as usual (here, the IEA New Policies Scenario) and not in a low-carbon scenario (here, the IEA 450 Scenario).

- **Capital intensity:** the average investment needed to produce each category of resource, displayed as the top (red, green, or blue) portion of each bar.

- **Rent intensity:** the difference between the total (capital and operating) cost of each category of resource and the average price per unit produced or emitted, which decreases from left to right as production costs rise.

Figure 1 above provides a guide for reading the cost curves, each of which contains many more "blocks", or resources, on the following pages. The x-axis represents production of each resource type, while the y-axis shows the cost of producing each unit of that resource type. Since our analysis is concerned with carbon lock-in, we present resource production in terms of Gt CO2 emitted once that resource is combusted (after accounting for non-combustion uses).

The full-coloured blocks at left represent fossil fuel production that would occur even in a low-carbon scenario. The lighter blocks at right (1) represent over-production; we assume for simplicity's sake that higher-cost resources would be the ones not produced. The black and grey blocks represent operating costs. The orange blocks (2) represent capital intensity – which, as noted earlier, increases the likelihood that a resource will be produced, once investment is made, even at low market prices.

Instead of orange here, the charts in Figures 2–4 use dark and light red (coal), green (oil), and blue (gas) to represent capital investment. Rent intensity (3) is expressed as a block of white space between the coloured blocks and the line for the average price.

Key findings

Not surprisingly, of the three fossil fuels, it is coal for which production would need to be scaled back the most in a low-carbon scenario, both as a share of production (34%) and in absolute carbon terms (about 5 Gt CO_2). At the same time, the analysis indicates that investments in coal production may also be the easiest to "unlock". As indicated by the areas of the coloured (red, green and blue) bars and light grey bars, coal resources are far less capital-intensive (less than 5 USD/t CO_2) than oil or gas, for which new fields require investments of 30 USD/t CO_2 or more. This indicates that sunk costs for infrastructure, and creditor concerns, may contribute less to lock-in for coal.

Coal is also far less rent-intensive on average, with most deposits yielding rents of less than 10 USD/t CO_2, while rents to oil and gas production average 50 USD/t CO_2 or more. This suggests that carbon pricing – or normal fluctuations in resource prices – could have a greater effect on coal than

on oil or gas production. With combined capital and production costs that are far closer to expected prices than those for oil and gas, coal mines are at far greater risk of being rendered uneconomic by carbon pricing. Thus, at least based on economic considerations, investments in coal production may create less "lock-in" risk than investments in oil or gas production.

Of course, social and political considerations – as well as local differences in project economics, including rents – might change the outlook. For example, other research has suggested that coal production is more labour-intensive than oil or gas, and that coal production interests have already been among the most powerful opponents of climate policies in both the U.S. and the EU. Furthermore, coal-fired power production (the demand side of coal markets) still presents a significant lock-in risk.[22] That said, planners concerned about carbon lock-in risks from fossil fuel supply investments may want to look at oil and gas before coal.

Oil is both the most capital-intensive and most rent-intensive fossil fuel, with average capital intensity of 44 USD/t CO_2 (16 USD/bbl) and rent intensity of 200 USD/t CO_2 (74 USD/bbl), when assessed across all barrels produced. This high rent intensity suggests that, for many oil deposits, carbon pricing would be less likely to affect production as substantially. The capital intensity of oil production ranges from 4 to 41 USD per barrel (11 to 112 USD/t CO_2), with

Figure 2. Coal production in 2030 in the BAU and low-carbon scenario, including over-production

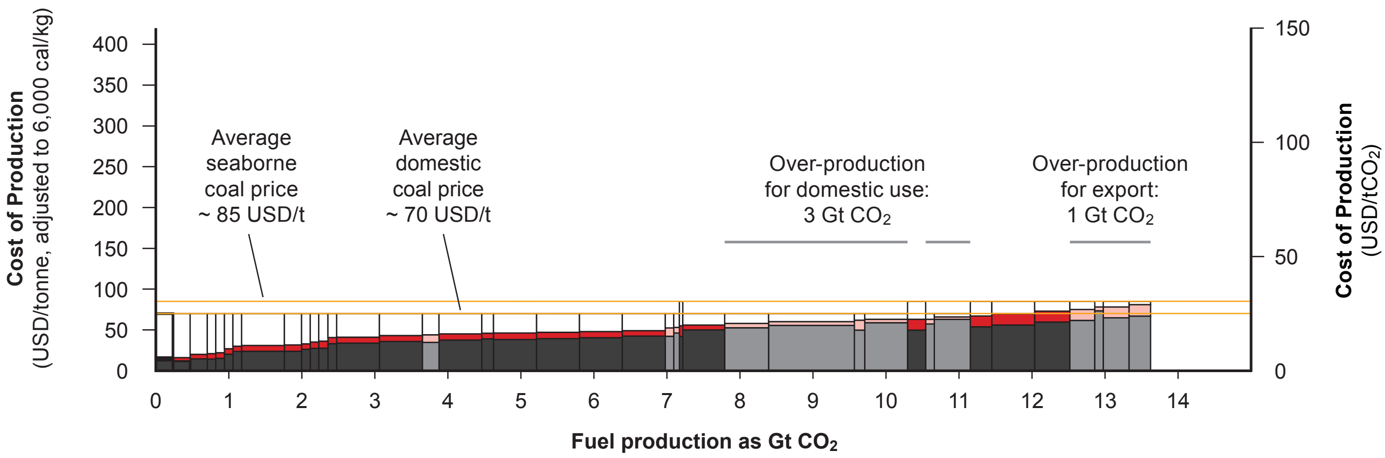


Figure 3. Oil production in 2030 in the BAU and low-carbon scenario, including over-production

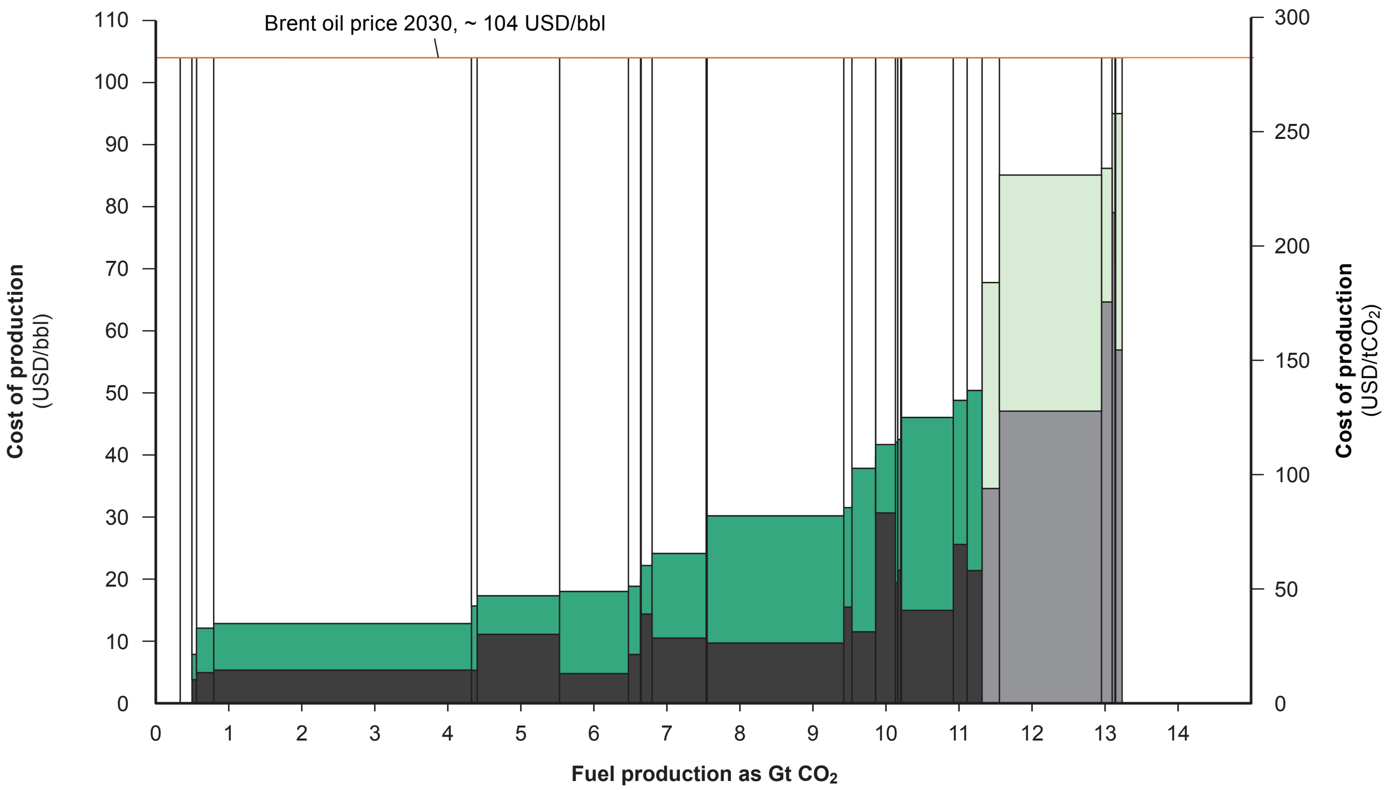
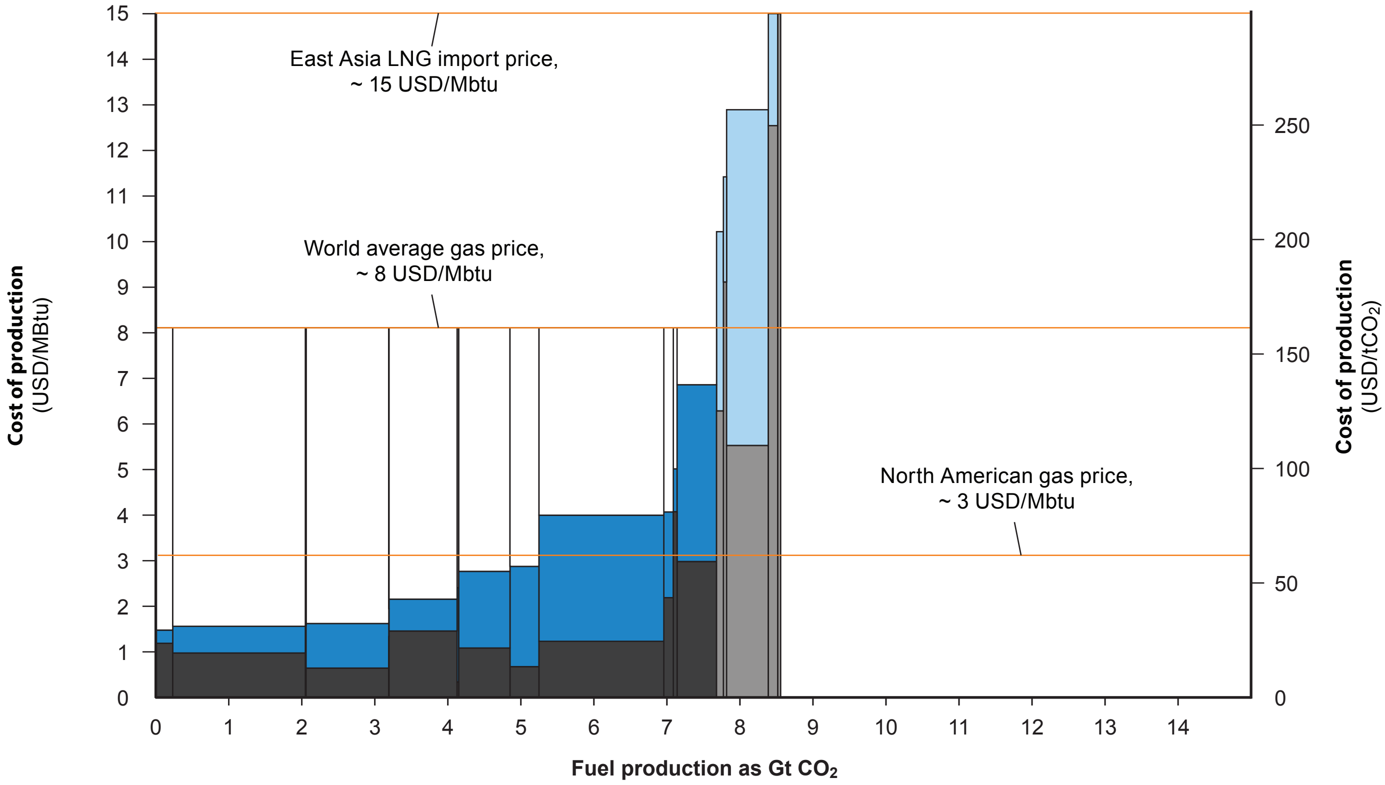


Figure 4. Gas production in 2030 in the BAU and low-carbon scenario, including over-production



significant investment required especially for higher-cost (currently not producing) offshore resources unlikely to be developed in a cost-efficient low-carbon scenario. Near-term investment in these resources could be substantial, creating momentum for future over-production.

For the barrels over-produced in 2030, our analysis shows a capital intensity of 97 USD/t CO_2 and rent intensity of 55 USD/t CO_2 – or 153 USD/t CO_2 combined (see Table 1), suggesting that those resources would be well-insulated from future price fluctuations or carbon pricing, once capital is invested. Overall, our analysis suggests that among investments in fossil fuels, those in oil production, especially in higher-cost, yet-to-produce resources, are most likely to increase carbon lock-in.

Looking deeper at offshore oil, our analysis indicates that production from yet-to-be made investments in this infrastructure would need be cut by half in 2030 in the IEA's 450 Scenario, relative to BAU. The Americas (North and South) represent the greatest source of over-production (nearly half). Capital investments such as these may deserve special scrutiny because, once oil platforms and other major fuel extraction infrastructure are in place, the marginal cost of producing each unit of resource drops to 50 USD/barrel or less (the operating cost – i.e. the black or grey portion of each bar in Figures 2–4). This insulates the resource from likely expected variations in fuel price, whether due to climate policy or normal market fluctuations.

Rent intensities for natural gas production can also be substantial (averaging 93 USD/t CO_2 or 5 USD/MBtu), though large variations in regional gas prices complicate the assessment of rents for gas, and the average values indicated in Figure 4 may not apply for regions where natural gas prices are very low (e.g. North America, with prices as low as 3 USD/MBtu) or very high (e.g. liquefied natural gas in East Asia, with prices as high as 15 USD/MBtu, as indicated in Figure 4). As with oil, yet-to-produce offshore gas resources

Table 1. Carbon lock-in assessment of over-produced fossil fuel resources

Resource Group	Fossil fuel over-production, 2030 (Gt CO_2 annually)	Production in low-carbon scenario relative to BAU in 2030	Average capital intensity (USD/t CO_2 over-produced)	Average rent intensity (USD/t CO_2 over-produced)	Capital + rent intensity
Coal	4.6	-34%	3	*	*
Of which, seaborne	1.0	-37%	5	$3	8
Oil	1.9	-14%	97	$55	153
Of which, offshore and not yet producing	1.4	-50%	104	$52	155
Gas	0.9	-10%	119	*	*
Of which, offshore and not yet producing	0.6	-27%	144	*	*

*We do not report average rent intensities for natural gas or for domestic coal, since unlike for oil and seaborne coal, there are wide variations in prices by region.

are the most capital-intensive, with over-produced resources averaging 144 USD/t CO_2 (7.4 USD/MBtu). They also are set to over-produce by the greatest quantity: 0.6 Gt CO_2 in 2030.

These findings depend on the year chosen (here, 2030) and the scenarios used (here, the IEA's New Policies and 450 scenarios). Thus, our analysis is just one possible outcome of such an exercise. Low-carbon scenarios that foresee greater reduction in oil consumption, for example, might suggest the need to further scale back capital-intensive oil investments. Indeed, lower oil price scenarios in Rystad Energy's assessment may foreshadow what might occur under even deeper low-carbon scenarios, as they also lead to a substantial scale-back of capital investment in onshore tight oil production, especially from not yet producing assets.[23]

Similarly, if an analysis year well beyond 2030 were chosen, some low-carbon scenarios might foresee significant availability of carbon capture and storage (CCS) facilities, thereby enabling higher levels of coal production, and thus less over-production relative to BAU. That said, our assessment of over-production of coal, oil, and gas in a 2030 time frame is broadly consistent with a recent meta-analysis of fossil fuel production in a low-carbon economy.[24]

Policy implications and conclusions

This paper presents a generalized approach for assessing carbon lock-in risk from investments in fossil fuel extraction, building on common approaches to energy scenario analysis and fossil fuel resource analysis. Using this approach and its three metrics – *over-production*, *capital intensity* and *rent intensity* – policy-makers can assess the consistency of plans for developing new fossil fuel resources, or infrastructure to support them, with climate protection objectives.

Our application of this approach at the global scale suggests that rents for coal extraction are low enough that, in principle, scaling down coal extraction may be within reach of climate policy – e.g. through carbon pricing at the point of extraction or through financial incentives.[25] Indeed, others have proposed policy mechanisms, such as supply-side cap-and-trade, designed to transition away from coal.[26]

In contrast, oil extraction is relatively profitable and, in many cases, capital-intensive. This suggests that strong financial interests may pose substantial barriers and tend to keep capital-intensive oil resources in production, even if later policy efforts (including carbon pricing) were to call for a transition away from oil.

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Close-up of a surface coal mine in Gillette, Wyoming.

The capital-intensive nature of new, unconventional and offshore oil developments, as identified here, suggests that near-term investments may bring resources online that will be especially difficult to unlock. Furthermore, some researchers have suggested that resource owners may deliberately speed up investment and production in the near term, while carbon prices are low or non-existent, so they can lock in and insulate resources against the loss of rents due to the eventuality of steeply increasing carbon prices.[27] Policy-makers concerned about carbon lock-in risks, but also eager to ensure that near-term energy needs are met, may want to try to steer investment towards less capital-intensive oil reserves.

More broadly, our analysis highlights the importance of identifying the potential for fossil fuel "over-production" and the capital and rent intensities associated with those resources. Policy-makers could then tailor policy measures to fit the capital and rent intensity of each type of resource. Where rent intensity is low, financial measures (such as carbon pricing and subsidy reform) may be particularly effective. For resources that are both rent- and capital-intensive, non-financial measures, such as quotas or limits on extraction (implemented through permitting decisions, for example), might be more effective. Further research is needed to better understand which approaches are most effective, and how they might be combined.

Of course, carbon lock-in risk is just one of many factors that policy-makers may consider in regulating the development of fossil fuel resources. Countries with substantial fossil fuel resources may have only a small subset of the high-risk resources assessed here. Or they may already be deeply "entangled", heavily dependent on fossil fuel extraction – or be counting on it for their future energy supply and economic development.

Applying this approach at the regional or national level is likely to raise questions about accounting and equity that policy-makers have yet to resolve. For example, some countries extract (and generate rents from) fossil fuels that are exported to other jurisdictions, where they release CO_2 emissions that are not generally attributed to the countries of origin.[28] By limiting extraction, such countries would forgo economic rents without getting "credit" for any emissions avoided. (Global CO_2 emissions would be avoided to the extent that the forgone production was not matched by production increases in other countries.)

The importance of fossil fuel extraction to some lower-income countries' development should also be carefully considered. Their policy-makers may rightfully note that many other countries have based economic development on fossil fuel energy. Thus, the application of this analytical approach at the regional and national scales would need to consider this concern, as well as possible relationships between the location (and forgone rents) of fossil fuels left in the ground and the financial responsibility for climate change mitigation.

Other researchers have suggested that policies to limit fossil fuel supply, such as supply-side caps, can increase the efficiency and effectiveness of demand-side measures to reduce

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A shale gas well in Pennsylvania, one of thousands developed in the state as part of the Marcellus Shale hydraulic fracturing boom.

CO_2 emissions as well.[29] Additional research is needed to clarify how supply-side policies can complement demand-side policies. This framework can contribute to that research by helping to shed light on the types of fossil fuel resource investments likeliest to create carbon "lock-in", and thus help policy-makers to develop well-targeted and effective supply-side climate strategies.

Endnotes

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For a quick overview of the scenarios, see: http://www.iea.org/publications/scenariosandprojections/. Note that the IEA also has a Current Policies Scenario that is a more classic BAU, assuming no changes from existing policies.

In line with the concept of carbon lock-in, we focus solely on CO_2 emissions from fossil fuel combustion, though we must note that other GHGs, notably methane, are released in the course of extracting and processing fossil fuels. Such emissions can often be reduced through cost-effective improvements in extraction and processing operations, however, and may thus be less "locked-in".

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The Maersk Intrepid, the first of four jack-up rigs built for 'ultra-harsh' environments, at the Keppel FELS shipyard in Singapore, before being mobilized to drill wells on the Martin Linge field development in the Norwegian North Sea.

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