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LETTER

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Abstract

The urgent need to accelerate the transition towards low-carbon energy is well understood. Government support for energy innovation has been an increasing focus of both policy and academic attention in recent years. The debate has focused on direct spending by governments on research and development (R&D). However, governments also support R&D indirectly, through tax credits. This source of government support has been overlooked in the academic and policy debate on energy innovation, in part because publicly available data on R&D tax credit expenditures typically do not enable the identification of spending specific to energy. This article provides the first published data on R&D tax credits in the energy sector, drawing on administrative data from Australia, Canada, Norway and the UK. This data shows that indirect support through tax credits can be a large source of support for innovation in fossil fuel extraction companies, though this differs by country. As a result, publicly available data on direct R&D spending by government can significantly understate government support for innovation in fossil fuel extraction. The article also presents patent data to show, for the UK and for Norway, that less than 5% of R&D activity in fossil fuel extraction firms is devoted to low-carbon technologies. The article concludes with the recommendation that governments should consider removing tax credit support for R&D activities that facilitate the extraction of fossil fuels.

1. Introduction

Considerable academic research and policy debate (Anadon *et al* 2017, Myslikova and Gallagher 2020) has focused on the role of publicly-funded research and development (R&D) for clean energy technologies. This debate has focused on direct expenditure by governments, often using data reported by countries to the International Energy Agency. However, this data excludes a further source of public support for innovation: R&D tax credits.

This article provides the first published data on R&D tax credit support to innovation in the energy sector. I present new administrative data from the UK, Australia, Canada and Norway, showing that R&D tax credits can be a significant source of public R&D support for energy technologies. As a result, publicly available data on direct government energy R&D spending can significantly understate actual government support for fossil fuel R&D. Taking these four countries as a whole in 2015, R&D tax credit support for fossil fuel extraction firms

was larger than direct R&D support to fossil fuel technologies: i.e. the data on direct R&D support, which is typically the focus of public policy debate on energy innovation, understated public R&D support for fossil fuel innovation by more than half in that year.

I also use patent data to show, for the UK and for Norway, that less than 5% of R&D activity in fossil fuel extraction firms is devoted to low-carbon technologies. I argue that governments should consider removing tax credit support for R&D activities that facilitate the extraction of fossil fuels.

2. Indirect government expenditure on energy R&D has been overlooked in the policy debate

In most large industrialised countries, direct government support for energy R&D (such as grants to firms, universities and public research institutions) has increasingly been targeted at low-carbon energy.

This is a result of a broad policy consensus about both the urgency of dealing with climate change and the importance of directed technical change in achieving that goal (Acemoglu *et al* 2012). This consensus is in part rooted in the awareness that innovation and R&D contributes to (or facilitates break-out from) a state of ‘carbon lock-in’ (Unruh 2000, Seto *et al* 2016), i.e. the path-dependent processes which make a quick switch to low-carbon energy difficult and costly. With a long-term perspective, it is clear that public subsidies directed towards low-carbon technologies are an important part of a robust climate policy mix (Stern 2007, Acemoglu *et al* 2012).

The policy debate, and associated research, has focused on questions related to direct public funding of energy R&D. Key policy questions have been as follows: how much should governments spend on energy R&D (Nemet and Kammen 2007, Myslikova and Gallagher 2020)? Which technology areas should be the priorities for spending (Grubler and Riahi 2010, Pugh *et al* 2011)? What is the appropriate balance of spending between R&D versus deployment support (Laleman and Albrecht 2014)? To what extent do public R&D vs demand-pull drive innovation outcomes (Nemet 2009)? All of these papers have made use of data on direct public funding of energy R&D. A common source of such data is the International Energy Agency database of energy R&D budgets, which allows analysis of R&D by technology over time in OECD countries.

In contrast, the role of indirect public support via R&D tax incentives has been almost completely overlooked in the climate policy debate and in studies relating to public R&D support. Yet indirect support via tax credits is in many countries a significant share of overall public support for R&D (Appelt *et al* 2016, OECD 2017). There is very little data about where that support goes, in terms of broad categories of energy technology, since data is only reported by tax agencies at the highest levels of sectoral aggregation, such as ‘mining and quarrying’ (see, for instance, the publications from the UK’s HMRC (2019)). As a result, the publicly available data on R&D tax credits does not enable an assessment of their significance as a source of taxpayer support to specifically energy-related activities. In light of the substantial debate about the appropriate volume and targeting of direct energy R&D expenditure, and the effects of that spending, it is striking that there is so little knowledge of the volume and distribution of indirect energy R&D support. This paper begins to address this gap in the policy debate.

It is worth noting that there is a robust global debate about subsidies to fossil fuel industries, including support for innovation. However, R&D tax credits are unlikely meet mainstream definitions of fossil fuel subsidies (OECD 2018, IEA 2019), since they are a financial aid available to all sectors of the economy and not specific to fossil fuels. While R&D tax

credits are a form of government support to fossil fuel companies that has been hitherto overlooked in the policy debate, they are not fossil fuel subsidies under these definitions. Similarly, there is an existing literature concerned with the use of tax credits to support the development of energy efficiency and renewables (e.g. Johnston 2019). However, this literature does not address R&D tax credits, which are the subject of this paper.

3. R&D tax credits as innovation policy

It is widely accepted that government support for R&D is necessary, because market failures associated with knowledge spillovers reduce the incentives for firms to conduct R&D to well below the socially optimal rate. Governments provide funding for basic science and research, often in universities or public research institutions, and most also provide support for R&D in firms, either through direct grants or through tax incentives.

There is an active policy debate about the importance of tax credits in stimulating an effective innovation system (Dechezleprêtre *et al* 2016). The argument in favour of tax credits over direct grants as a means of supporting R&D is intuitive: private firms are best able to determine which R&D projects are most likely to generate valuable results, bringing together technological opportunities with market demands. Under this perspective, government lacks the knowledge to select the best R&D projects to support, and the choice should therefore be left as much as possible to the private sector. Moreover, tax credits are more straightforward to administer: governments do not need to select projects or run competitive processes for the allocation of funds, nor do they need to make decisions about the priority areas of R&D to pursue.

Yet there are also concerns about the additionality of R&D tax credits. Would the firms receiving R&D tax credits have conducted the R&D anyway? If so, the subsidy is poorly targeted, and simply represents a transfer from the public to private sector. Most studies do find evidence that R&D tax incentives induce additional R&D expenditure, particularly when support is maintained over the long run (Appelt *et al* 2016). For these reasons, many countries have expanded the use of R&D tax credits in recent years (Appelt *et al* 2020).

As well as concerns about additionality, the apparent neutrality of R&D tax credits is less straightforward than it might appear. With a tax incentive at a single rate for all firms, there is clear evidence that large incumbent firms (Bravo-Biosca *et al* 2013) and those in particular sectors benefit most (Castellacci and Lie 2015). As a result, governments have tended to differentiate support for large vs small firms, or to put caps on the total value that can be received by any individual firm.

In a few cases, governments have put in place non-neutral R&D tax incentives, providing additional support to strategic areas of science and technology. These are cases in which governments have sought to align the benefits of tax credits with a recognition that market-driven private R&D priorities may fail to meet broader social priorities that are poorly represented in markets. Between 2003 and 2017, the UK offered a higher rate of R&D tax credits for research on vaccines, malaria, tuberculosis and HIV/AIDS (HMRC 2016). Several US States have also used higher rates of R&D tax credits as part of a regional industrial strategy. For example, Wisconsin offers higher rates of tax credits for R&D on internal combustion engines and energy-efficient products (State of Wisconsin 2017). The administrative mechanism in such cases is typically that the taxpayer submits a short statement on the focus of the R&D projects for which they are seeking tax relief, to demonstrate that the R&D-related expenditure is eligible for the technology-specific rate of relief.

4. Examining indirect public support for fossil fuel extraction: methods and data

4.1. Country selection

Data was sought from OECD countries that met both of the following two criteria. First, a significant fossil fuel extraction sector, defined as fossil fuel rents >1% of GDP in any year since 2010, based on data from the World Bank (2021). Second, extensive use of R&D tax credits as an instrument supporting innovation, defined as higher R&D tax credit support than the OECD median in 2015 (OECD 2015). Data was sought from tax agencies or statistical agencies in the UK, Netherlands, Canada, Australia, and Norway. The Dutch tax office declined to provide data, citing confidentiality concerns. The countries selected differ in the degree to which their economies are fossil fuel intensive: fossil fuel rents exceeded 10% of Norway's GDP since 2010, whereas in the UK fossil fuel rents have been lower than 1.14% of GDP during this period.

Each country has made commitments to reduce greenhouse gas emissions, both internationally under the Paris Agreement, and through domestic legislation. They have also all made commitments to increase clean energy innovation: all are members of the international 'Mission Innovation' initiative which aims to accelerate the development and diffusion of low-carbon technologies.

The countries differ in the stringency of their climate policy frameworks. Both Norway and the UK have had carbon pricing systems (including the EU Emissions Trading Scheme) in place for more than a decade. Australia and Canada have had less consistent climate policy, with variation between states/provinces, and over time. Australia and Canada have often been criticised as having relatively weak

targets and policies (see, e.g. reports of Climate Action Tracker or the Climate Policy Performance Index, (Burck *et al* 2014, Climate Action Tracker [no date](#))). However, it is not straightforward to compare climate policy ambition or stringency in a way that adequately accounts for national circumstances (Aldy *et al* 2017, Höhne *et al* 2018).

4.2. Data collection

R&D tax credit data were provided by the HMRC Datalab in the UK, the Canada Revenue Agency, the Australian Tax Office and Statistics Norway. Data was provided on the value of R&D tax credits received by companies whose principal classification code is, or has recently been, related to fossil fuel extraction. Industry classification codes differ in each of the countries, and the codes used are shown in table 1.

Data on direct public expenditure on energy R&D, by technology, was taken from the International Energy Agency.

In order to assess the extent to which fossil fuel extraction companies direct their R&D towards low-carbon technologies, I also examined patent data. Patent data was analysed using the AMADEUS database from the Bureau van Dijk, which until July 2020 included linked patent data drawn from the European Patent Office's PATSTAT database. Fossil fuel extraction companies were identified using sectoral classification codes relating to fossil fuel extraction. Patents filed by those firms were then identified, based on the patent-company linkages established by the Bureau van Dijk. These firm-patent linkages have been found by other researchers to be reliable (Dechezleprêtre *et al* 2016).

When registered, patents are given codes that describe the specific areas of technology to which they relate. In this study, I use patent codes to explore the broad areas of technology that are the focus of inventive activity in fossil fuel extraction firms.

The subset of patents relating to climate change mitigation technologies was identified using the Y02 classification system. The Y02 classification system was developed by patent offices to facilitate research into technological innovation relevant to climate change. Patents in the PATSTAT database that relate to climate change mitigation technologies have been tagged with patent codes using relevant Y02 categories, in addition to the normal patent codes that describe their technology domain (Haščič and Migotto 2015). For example, patents specific to carbon capture and storage (CCS) are tagged with a Y02C code, but may also have other codes related to gas separation or earth drilling.

The patents used are all filed patents, with family size ≥ 2 (i.e. patents that have been filed in at least two countries), with filing dates between 2012 and 2019. Patents are identified based on company applicant, so for example those analysed for Norway are patents filed globally by companies based in Norway. For

Table 1. Industry classification codes used to identify fossil fuel extraction firms.

Australia	Norway	Canada	UK
ANZIC codes	NACE codes	NAICS codes	SIC codes
06000 (coal mining)	05 (mining of coal and lignite)	211 (oil and gas extraction)	05 (mining of coal and lignite)
07000 (oil and gas extraction)	06 (extraction of crude petroleum and natural gas)	2121 (coal mining) 213111 (drilling oil and gas wells)	06 (oil and gas extraction)
—	09.10 (support activities for oil and gas extraction)	213112 (support activities for oil and gas operations) 213113 (support activities for coal mining)	0910 (support activities for oil and gas extraction)

Table 2. Direct and tax credit support for fossil fuel R&D in the four countries, in m\$ USD (nominal prices).

Government support for R&D in m\$ USD	2014	2015
Tax credits	423	387
Direct support	586	358

large integrated oil and gas companies, it is possible that the patents identified have been generated from R&D activities outside their home countries.

5. Publicly available data understates government support for innovation in fossil fuel extraction

Here, I present previously unpublished data from the tax offices of Australia, Canada, Norway and the UK. The data shows the amount of tax relief received for R&D by firms whose principal industry classification is related to fossil fuel extraction. I compare the support for fossil fuel innovation via tax credits to support for fossil fuel R&D directly funded by governments. Taking all four countries together, in 2014 and 2015 tax credit support is similar in scale to direct support for fossil fuel technologies (see table 2). These are the only 2 years for which data from all four countries was available. In other words, for these 2 years at least, publicly available data significantly understates government support for innovation in fossil fuel extraction.

However, there is considerable variation between countries, as shown in figure 1. In Australia, the majority of taxpayer support to fossil fuel R&D has come in the form of tax credits in most of the years for which data is available. In contrast, very little R&D support for fossil fuels comes as tax credits in Norway.

The variations between countries can partly be explained by differences in the design and generosity of R&D tax credit policies. In Norway, tax credits are capped such that no single taxpaying firm can claim more than certain limit (in 2015 this was 33 m NOK, around \$3.7 m USD). In contrast, in Australia, the rate of R&D tax relief declines after an expenditure

threshold of AUS\$100 m (around \$75 m USD), but there is no upper limit on the total claim (OECD 2020)¹. In the oil and gas sector, where a relatively small number of large oil majors perform a substantial share of R&D, the level of such caps is expected to have a strong influence on the overall amount of tax credit support.

Given the short time-series, it would be unwise to over-interpret the variation seen over the time period observed. However, it is clear that the volumes of both indirect and direct support to fossil fuels underwent substantial changes during this period.

5.1. Changes in direct R&D support

Canada, Australia and Norway all saw clear reductions in direct public expenditure on fossil fuel R&D between 2012 and 2016. Expectations for CCS technology declined during this period, and IEA data makes clear that the reduction in direct R&D funding for fossil fuels is largely related to declines in funding for CCS technologies (figure 2). Australia and Norway substantially reduced CCS expenditure between 2012 and 2016, by 93% and 55%, respectively. Similarly, Canada reduced expenditure on Integrated Gasification Combined Cycle (IGCC) technology by more than 90% between 2012 and 2016. Canada's IGCC investments had been part of a clean coal programme that was closely linked with expectations around CCS (Reeve and Ham 2005).

5.2. Changes in indirect R&D support through tax credits

There were also pronounced changes in the value of R&D tax credits received by fossil fuel extraction firms during the period observed. As shown in figure 1, the UK and Norway saw increases, with a doubling of R&D tax credit support observed in both countries, while Canada and Australia experienced declines (Australia's small expenditures in the first year are likely to be a result of the newness of the R&D tax credit scheme, which was introduced

¹ Note that since the period under study, the Australian system has been adjusted, and the ceiling is now AUS\$150 m.



Figure 1. Tax credits received by fossil fuel extraction companies (blue bars) and direct funding to fossil fuel technology R&D by governments (orange lines), in m\$ USD. Data for direct budgets is from the International Energy Agency; tax credit data is from national tax authorities. Where no tax credit data is shown, this means data is missing; there are no zero values for tax credits in any of the countries or years shown.

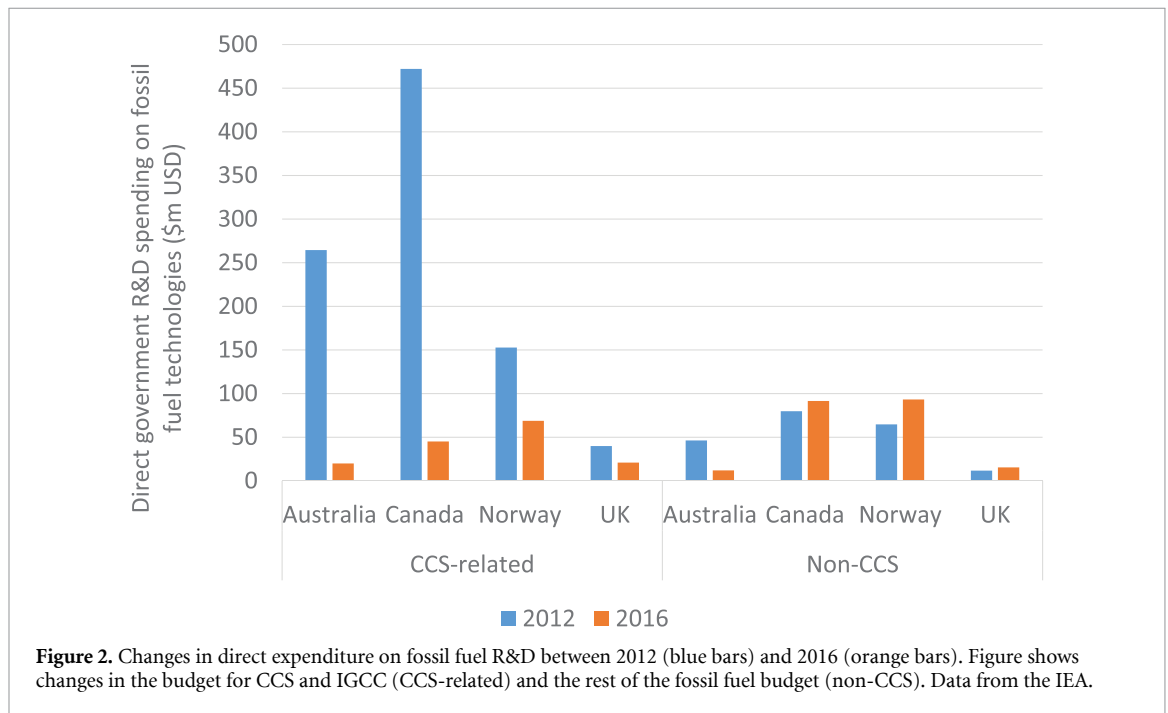


Figure 2. Changes in direct expenditure on fossil fuel R&D between 2012 (blue bars) and 2016 (orange bars). Figure shows changes in the budget for CCS and IGCC (CCS-related) and the rest of the fossil fuel budget (non-CCS). Data from the IEA.

in 2012). Two driving forces might be expected to explain much of these trends. First, changes in R&D tax policy could result in higher or lower levels of support for a given volume of R&D, and could drive the R&D investment choices of firms. Second, changes in fossil fuel prices could change the incentives for conducting R&D. Given the short time series and inconsistent data availability between countries, it is not possible to provide a robust analysis of the relative importance of these factors, but some basic observations can be made.

Survey data provides some insight into overall levels of R&D expenditure on fossil fuels in these four countries, regardless of whether firms applied for tax credit support (ONS 2017, Australian Bureau

of Statistics 2019, Statcan no date, Statistics Norway no date). In Canada, Norway and Australia, overall business R&D in oil and gas fell from a peak in 2013. Though UK data is limited to the years 2014 and 2015, oil and gas R&D also fell in this period. These changes coincide with declines in international oil prices, from a peak in 2013. Previous research (Daniels and Johnson 2019) has found that innovation (proxied by patent applications) in the oil and gas sector is responsive to prices. Data on coal mining R&D is only available from Australia, and this also fell during the period. Coal mining R&D is likely to be a negligible proportion of the UK and Norwegian fossil fuel extraction R&D, given the small role of the sectors in those economies.

In the UK and Norway, despite the overall reductions in R&D performed by the sector, tax credits for fossil fuel R&D increased between 2013 and 2016. Both the UK and Norway saw policy changes that increased the generosity of R&D tax incentives during the period. In Norway, the maximum value of R&D tax credits that any single firm can claim was raised repeatedly during this period, from a possible maximum of 11 m NOK in 2013 to 40 m NOK in 2016 (Rybalka 2019). Similarly in the UK, tax credit schemes were made more generous for both large and small firms during the period (HMRC 2019). The finding that fossil fuel R&D tax credit volumes rose while overall R&D from the sector fell suggests that the tax policy changes are a plausible explanation for at least some of the observed increases in tax credit support.

In both Canada and Australia the reductions in R&D tax credit volumes coincide with policy changes that reduced the rates of support through R&D tax credits (Australian Government 2016, OECD 2019). In Australia, this involved the introduction of a cap on the maximum claim for individual tax payers (of \$100 m). However, in both Canada and Australia, data shows that total economy-wide R&D tax credits declined only marginally (Australian Taxation Office 2019, Statcan 2019), suggesting that the more pronounced decline in fossil fuel R&D tax credits may be more readily explained by the fall in oil prices, and consequent reductions in firm R&D budgets.

5.3. R&D tax credit support for fossil fuel innovation can be large relative to total direct energy R&D budgets

Figure 3 shows tax credits for R&D in fossil fuel firms in comparison to total government direct budgets for energy R&D across all technologies. In Australia, the scale of R&D tax credits is significant in comparison to the total direct energy R&D budget, exceeding it in 2014 and 2015. In Canada and the UK, R&D tax credits for fossil fuels are between 10%–19% (Canada) and 10%–17% (UK) of the total direct energy budget for the years in which data is available. Norway has a relatively large energy R&D budget and very small R&D tax credit support to fossil fuel extraction.

I present data only on R&D tax credits received by fossil fuel extraction firms. The scale of R&D tax credit support to clean energy technologies is not known, and is an important question for future research. In particular, it is not known whether tax credits disproportionately benefit fossil fuel technologies.

5.4. R&D activities of fossil fuel extraction firms are largely directed towards high-carbon technologies

In the data presented above, I have identified fossil fuel extraction firms using industry classification

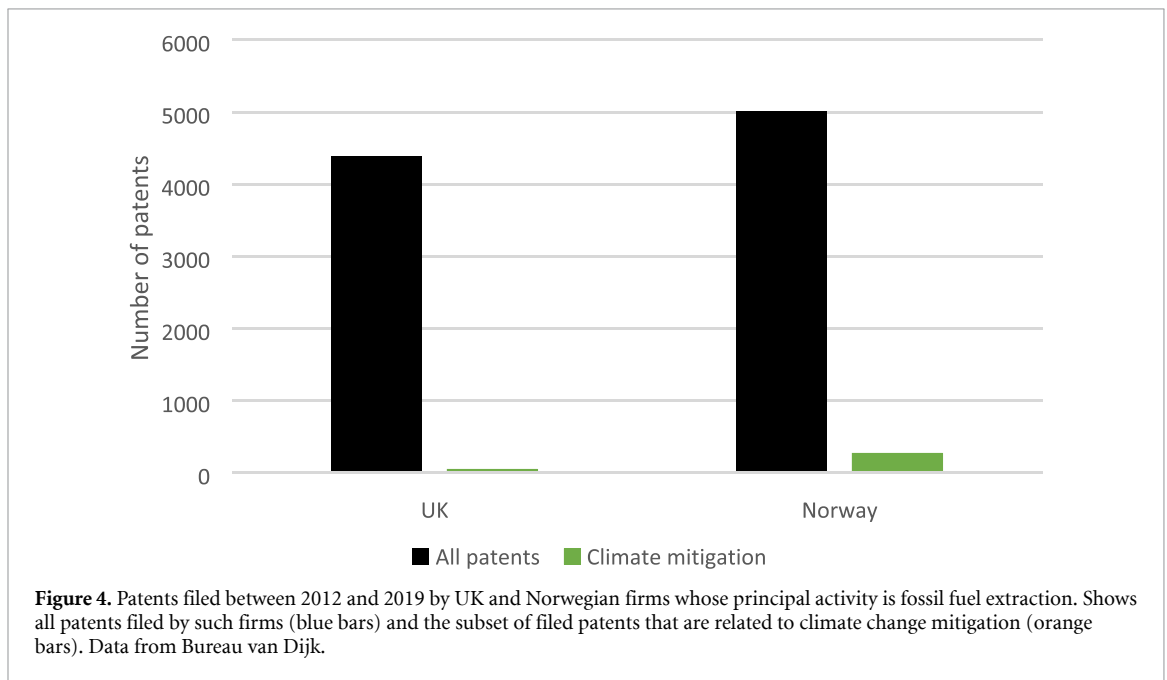
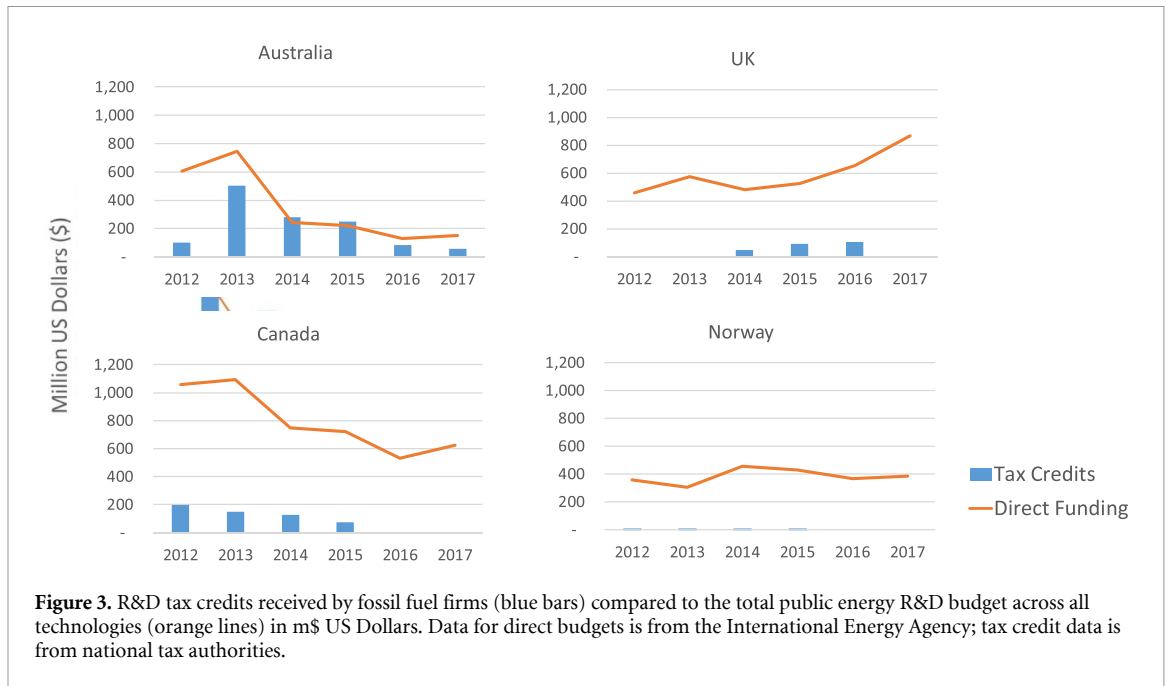
codes. However, many firms whose principal activities are related to fossil fuels are also involved in low-carbon energy technologies. Indeed, it is in principle possible that these firms focus their R&D activities towards low-carbon energy sources. Here I use patent filing behaviour to explore the extent to which the R&D activity undertaken by fossil fuel extraction firms supports climate change mitigation. The analysis presented here focuses on firms in Norway and the UK. Data from Orbis IP confirms similar patterns for Australia and Canada, but these data cannot be shown for contractual reasons.

Patent filing activity has previously been used by a number of studies as a proxy for the technological focus of R&D spending (Wiesenthal *et al* 2012, Pasimeni *et al* 2019). The European Patent Office has tagged patents related to climate change mitigation in its PATSTAT database, using the Y02 code. Using that data, linked to firms in the Bureau van Dijk's AMADEUS database, I have identified the share of patents for climate change mitigation technologies in the patent portfolios of companies whose principal industry classification is in fossil fuel extraction.

The data is presented in figure 4, which shows that the overwhelming majority of patents are not related to climate mitigation. Of the 9398 patents filed by UK and Norwegian fossil fuel extraction firms since 2012, only 3% are related to climate mitigation. This evidence strongly suggests that fossil fuel extraction firms in the UK and Norway were not devoting a substantial share of R&D activity towards climate mitigation objectives during the period for which patent data was collected (2012–2019).

During the past few years, several large fossil fuel extraction companies have announced initiatives to diversify and increase their involvement in low-carbon energy technologies. For example, Statoil changed its name in 2018 to Equinor, as part of a strategic shift to a broader range of energy sources. However, such changes are not reflected in an increase in clean energy patenting during the period observed. In contrast, the period shows a decline over time in the share of patents filed by fossil fuel extraction firms that are related to climate change mitigation (see figure 5).

The patent filing behaviour of these firms suggests a divergence in R&D priorities between public funders of energy R&D and fossil fuel extraction firms. Data reported to the IEA indicates that 40%–86% of direct funding for fossil fuel R&D by the UK and Norway since 2012 was focused on carbon capture and storage. Note that much of this is likely to have been conducted within universities and public research agencies rather than in firms. The patent filing behaviour of fossil fuel extraction companies suggests that they are much less focused on CCS technology: only 1.6% of patents filed by UK and Norwegian fossil fuel extraction companies between 2012 and 2019 relate to CCS.



Unsurprisingly, the most common patent codes assigned to inventions by fossil fuel extraction firms are those relating to fossil fuel extraction and processing (see table 3). For both Norway and the UK the dominant inventions by fossil fuel extraction companies are related to drilling technologies (identified by patent code E21B, which accounts for 56% of patents in the UK and 62% in Norway).

The subset of patents associated with climate change mitigation also features drilling technologies (E21B accounts for around a third of these patents), most of which are related to carbon capture and storage, as well as some examples of geothermal energy technologies. As shown in

table 4, other prominent patent codes include those relating to wind energy (F03D) and gas separation (B01D—again linked to carbon capture and storage).

5.5. R&D tax credit data reported in this study are conservative: true values may be higher

For the UK, Australia and Canada, the data reported here are likely to understate the true levels of tax credit support for R&D related to fossil fuel extraction.

In this study, I have used industry classification codes to identify firms active in fossil fuel extraction, using the industry codes that described the firms’ ‘main activity’ during the period in which they

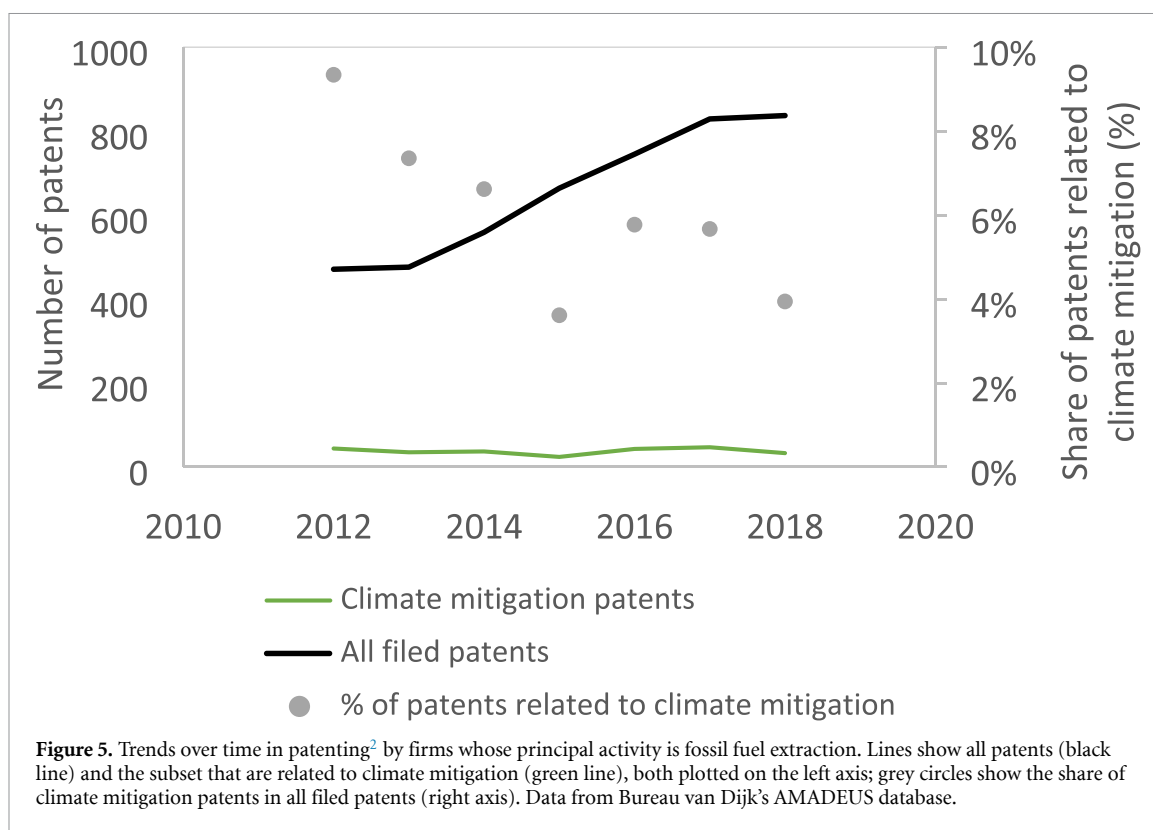


Figure 5. Trends over time in patenting² by firms whose principal activity is fossil fuel extraction. Lines show all patents (black line) and the subset that are related to climate mitigation (green line), both plotted on the left axis; grey circles show the share of climate mitigation patents in all filed patents (right axis). Data from Bureau van Dijk’s AMADEUS database.

Table 3. Most frequently observed patent codes among all patents filed by fossil fuel extraction companies. IPC patent codes are those set out in the International Patent Classification of the World Intellectual Property Organisation.

IPC patent code	Brief description	Share of all patent applications from the UK and Norwegian fossil fuel extraction firms (<i>n</i> = 9022)
E21B	Earth or rock drilling, covering methods and technologies for drilling for oil and gas	59%
F16L	Pipes and tubing	12%
G01V	Geophysics (e.g. imaging and detection technologies)	8%
B63B	Ships and vessels, associated with the offshore nature of the UK and Norwegian oil and gas industry	5%
C09K	Chemical compositions for drilling of boreholes or wells	4%
G01N	Methods and technologies for analysing the chemical or physical properties of materials	4%
C07C	Acyclic or carbocyclic compounds, particularly preparations of hydrocarbons	3%
C10G	Cracking hydrocarbon oils; production of liquid hydrocarbon mixtures	2%

received tax credits. Analysis of microdata for the UK suggests that the numbers reported using this approach may be an underestimate.

Each year, firms report the SIC code associated with their ‘main activity’. The microdata reveals that several of the firms in the sample change the SIC code that they report over the years. For example, this may include large integrated oil and gas companies headquartered in the UK switching their classification

from ‘extraction of oil and gas’ to ‘activities of head offices’. Similarly, engineering services companies specialising in equipment for oil and gas extraction may switch from ‘support activities for oil and gas extraction’ to ‘engineering design activities for industrial process and production’. It is likely that the activities of these firms do not always change as much as the SIC changes suggest, and that often the firms remain involved in fossil fuel extraction, even if it is no longer their main activity. The result is that the data presented in this paper are likely to be underestimates. This is likely to be true for all of the countries examined.

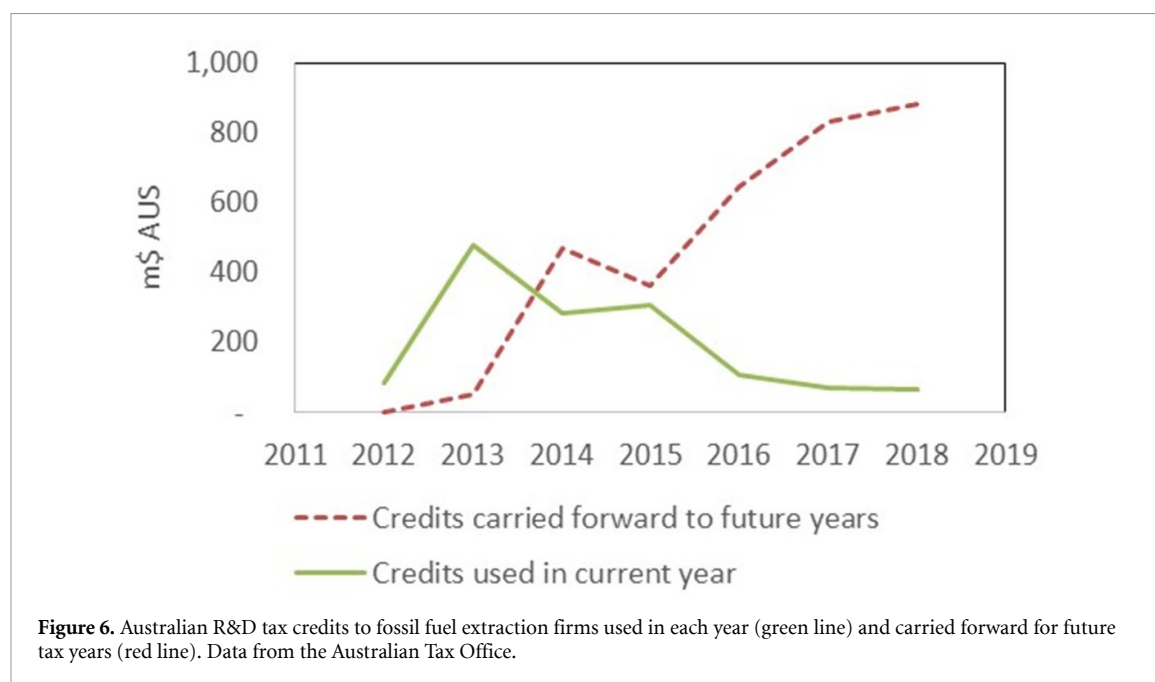
Note that only data from 2012–2018 is shown. The data were collected in 2020, and because of lags in patent publication, only data for the first half of 2019 is represented in the dataset.

Table 4. Most frequently observed patent codes among climate-mitigation patents filed by fossil fuel extraction companies. IPC patent codes are those set out in the International Patent Classification of the World Intellectual Property Organisation.

IPC patent code	Brief description of the IPC code	Share of all Y02 patent applications from the UK and Norwegian fossil fuel extraction firms ($n = 321$)
E21B	Earth or rock drilling, covering methods and technologies for drilling for oil and gas	36%
B01D	Separation technologies (most with this code are linked to CCS in the sample)	24%
F03D	Wind turbines	15%
B65G	Conveyors, warehousing, and pipelines	11%
C09K	Compositions for drilling	8%
H02J	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy.	7%
F23J	Removal or treatment of combustion products or combustion residues; flues (all patents with this code in the sample are CCS-related)	5%
C10L	'Fuels not otherwise provided for' in the IPC classification—includes LPG, synthetic natural gas, and gas clean-up technologies	4%

Table 5. Comparison of tax credits comparing a narrower and broader scope of 'fossil fuel extraction firms' (millions GBP).

	2014 and 2015	2015 and 2016
Firms with a fossil fuel extraction SIC code between 2014 and 2017	£26.7	£55.1
Firms with a fossil fuel extraction SIC code at any point from 2007 to 2017	£38.4	£79.4



An alternative approach would be to include all firms that had a fossil fuel extraction SIC at some point in the past decade, since this would capture firms involved in oil and gas but with a different 'main activity' during 2014–2017. It is not known how many of the firms that no longer listed fossil fuel extraction as a main activity continued to be substantially involved in fossil fuel extraction, but it is likely to be

non-negligible. Access to the UK microdata made it possible to examine this alternative, broader scope.

In table 5, I present the original UK data (in which data is based on the SIC code reported during 2014–2017) alongside the results when a broader scope is used. The table shows that this broader scope results in a substantial increase in the amount of R&D tax credits, of around 40%.

Data from Australia may also be an underestimate, because of the nature of the Australian tax credit regime. Australian R&D tax credits may be carried forward for use in future years. In this paper, I have counted only those R&D tax credits that are used in each year. These represent the direct financial benefit received by firms in terms of tax relief or tax refunds in a given year. However, the carry-forwards can be a significant tax asset for firms, since they allow firms to reduce their tax liabilities in future. Carry-forwards are not time-limited in the Australian tax system (OECD 2020), and the cumulative carry forwards held by fossil fuel extraction firms are shown in figure 6. This shows a growing tax asset held by Australian firms involved in fossil fuel extraction.

Finally, the data from Canada is also likely to be an underestimate of R&D tax credit support to innovation in fossil fuel extraction, for two reasons. First, statistical disclosure concerns prevented the release of data from firms whose principal industrial classification is 'coal mining', 'support activities for coal mining', or 'support activities for oil and gas operations'. The scope of included activities reported in the Canadian data is thus smaller.

Second, data for Canada is based on the federal R&D tax credit (the Scientific Research and Experimental Development tax incentive). Several provinces and territories also run their own R&D tax incentives, including those that have significant fossil fuel extraction, such as Alberta and Saskatchewan. Tax credits claimed under a provincial system reduce the eligible expenditures for the federal R&D tax credit, and as a result the federal total numbers reported here are likely to understate indirect taxpayer support for R&D in Canada.

6. Discussion and conclusions

R&D tax credits as a source of support to business R&D have been growing in recent years across the OECD (Appelt *et al* 2016). In principle, tax credits are an administratively straightforward way of providing incentives to R&D, while leaving decisions about which R&D projects generate most value to private firms that have the best information about market opportunities.

However, a large and diverse literature emphasises the importance of 'lock-in' and path dependence in technological change related to the environment (Geels 2002, Seto *et al* 2016). It is increasingly clear that innovation must be directed towards low-carbon energy if society is to avoid an environmental disaster (Acemoglu *et al* 2012). The idea of path-dependence in innovation has long been seen as a strong justification for technology-specific policies to combat climate change, alongside market-based and regulatory instruments (Stern 2007).

As a result of wide acceptance of the need to direct innovation to tackle climate change, governments around the world—including the four examined in this paper—have committed to increase investments in low-carbon energy. However, government support for innovation in fossil fuel extraction is likely to undermine efforts to redirect innovation towards low-carbon technologies and systems. Improved fossil fuel extraction technologies are likely to make fossil fuels cheaper and more widely available, reducing the competitiveness of low-carbon alternatives. Acemoglu *et al*'s model of directed technical change makes clear that continued public support for 'dirty' R&D can raise the total costs of achieving decarbonisation, by further contributing to lock-in. Their work highlights that there is a strong public policy case for re-directing subsidies for innovation away from 'dirty' innovation towards low-carbon technologies. Taxpayer support to R&D in fossil fuel extraction thus contributes to lock-in. The results presented here show that the scale of such support is relatively large compared to direct energy R&D budgets.

Governments may wish to fund innovation in fossil fuel extraction for a number of reasons, including safety, improved environmental performance and lowering the costs of fossil-derived energy. However, current fossil fuel extraction technology already enables the use of more fossil fuel than is compatible with achieving globally agreed climate change goals (McGlade and Ekins 2015). I conclude that governments should consider eliminating R&D tax credit support for technologies that facilitate fossil fuel extraction.

R&D tax incentives have typically been neutral with regard to technology and sector, and eliminating R&D tax credit support specifically for fossil fuel extraction would pose administrative challenges. However, technology-specific R&D tax credit regimes do exist. In Wisconsin, taxpayers separately identify R&D expenditure related to specific technology areas that have been prioritised by the state (specifically internal combustion engines and certain energy efficient products), and receive the higher rate of tax credits for these activities. The existence of such technology-specific schemes (which are found in many US States, and which for a time existed in the UK for vaccine research) suggest that it is administratively possible to differentiate R&D tax credit support by technology area. There is a need for further research to assess the feasibility of restricting R&D tax credits for technologies that facilitate fossil fuel extraction.

It is important to note that R&D tax credit support for fossil fuel extraction is also likely to be an important phenomenon in several industrialised countries not included within the sample. Several other OECD and non-OECD countries that produce fossil fuels make considerable use of R&D tax

credits as a method of supporting business innovation, including Brazil, the Netherlands and South Africa. The US also uses R&D tax credits, though these are less generous than in many other OECD countries. Each country has different rules over access to administrative data on R&D tax credits. Further research in this area would be valuable in revealing the global scale of indirect support to innovation in fossil fuel extraction.

An additional question for future research is to examine the level of R&D tax credit support for low-carbon innovation. The lack of sector-specific industry codes for low-carbon and renewable energy makes it difficult to identify the value of this support from existing datasets. Considerable further work would be required to reveal whether support for fossil fuel extraction is disproportionately larger than that for low-carbon energy.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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