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SYNTHESIS ARTICLE

The threat to climate change mitigation posed by the abundance of fossil fuels

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ABSTRACT

This article analyses the trends in primary demand for fossil fuels and renewables, comparing regions with large and small domestic fossil fuel reserves. We focus on countries that hold 80% of global fossil fuel reserves and compare them with key countries that have meagre fossil fuel reserves. We show that those countries with large domestic fossil fuel reserves have experienced a large increase in primary energy demand from fossil fuels, but only a moderate or no increase in primary energy from renewables, and in particular from non-hydro renewable energy sources (NHRES), which are assumed to represent the cornerstone of the future transformation of the global energy system. This implies a tremendous threat to climate change mitigation, with only two principal mitigation options for fossil-fuel-rich economies if there is to be compliance with the temperature goals of the Paris Agreement: (1) leave the fossil fuels in the ground; and (2) apply carbon capture and storage (CCS) technologies. Combinations of these two options to exploit their respective possibilities synergistically will require strong initiatives and incentives to transform a certain amount of the domestic fossil fuel reserves (including the associated infrastructure) into stranded assets and to create an extensive CCS infrastructure. Our conclusion is that immediate and disruptive changes to the use of fossil fuels and investments in non-carbon-emitting technologies are required if global warming is to be limited to well below 2°C. Collective actions along value chains in business to divert from fossil fuels may be a feasible strategy.

Key policy insights

- The main obstacle to compliance with any reasonable warming target is the abundance of fossil fuels, which has maintained and increased momentum towards new fossil-fuelled processes.
- So far, there has been no increase in the share of NHRES in total global primary energy demand, with a clear decline in the NHRES share in India and China.
- There is an immediate need for the global community to develop fossil fuel strategies and policies.
- Policies must account for the global trade flow of products that typically occurs from the newly industrialized fossil fuel-rich countries to the developed countries.

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Fossil fuels; renewables; CO_2 mitigation; CCS; energy demand

Introduction

Under the 2015 Paris Agreement, the global community has agreed to limit global average temperature increase to 'well below' 2°C above pre-industrial levels, and to pursue efforts to stay below 1.5°C warming (UNFCC, 2017). This calls for drastic emission cuts up to and beyond 2050. Based on analysis presented by Rogelj et al. (2015), to achieve this goal, Rockström et al. (2017) propose a halving of gross anthropogenic CO_2 emissions every decade (from 2020) together with immediate ramping up of carbon removal to reach net-zero emissions after 2050.

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About 70% of total global GHG emissions are in the form of CO_2 due to combustion of fossil fuels (Olivier, Peters, & Schure, 2017), and there are only two main options on the table to significantly limit their contribution to global warming: To leave the fossil fuels in the ground or to apply carbon capture and storage (CCS) technologies (and, of course, a combination of these).[1] Some of the required reductions in emissions from fossil fuels may be compensated for by negative emissions from bioenergy CCS (BECCS), afforestation and direct air-capture. Nevertheless, these are options associated with large uncertainties with respect to their costs and possible magnitude of contribution (cf. Fuss et al., 2014; Larkin, Kuriakose, Sharmina, & Anderson, 2017) and lack of policy instruments incentivizing negative emissions technologies (Honegger & Reiner, 2017). Since it is highly likely that *net* emissions must be negative in the second half of the century to limit warming to well below 2°C, emissions from fossil fuel use must indeed approach zero in the early second half of this century, which can only be achieved by the two above-mentioned fossil fuel options.

Although renewable sources of energy have undergone rapid expansion over the last decade (EPIA, 2014; GWEC, 2016, 2017; REN21, 2016), the share of fossil fuels in global energy demand remains at around the 80% mark. At the same time, large reserves of fossil fuels, especially coal, remain unexploited. To achieve the 2°C target will therefore require a disruptive change in the use of fossil fuels and in accelerating investments in alternatives to these fuels, in particular renewables. It seems clear that renewable energy policies have not been sufficient to ensure that the fossil fuels are left in the ground to the extent required. Thus, there is a need to analyse trends in fossil fuel use in more detail as a basis for understanding what is required from future policies to reduce fossil fuel supply. The aim of this article is therefore to explore the relationship between fossil fuel endowments (national fuel reserves) and trends in the use of fossil fuels and renewable energy. We do so focussing on 10 individual countries and the EU and Middle East as separate regions, comparing the situation of countries that are rich in fossil fuel endowments, with those that are less well endowed. From this, we assess *what can be expected* with respect to future climate action commitments in key countries with large fossil fuel reserves. The article also discusses the need for fossil fuel strategies and policies, and thereby aims to spur further work on strategies to incentivize and accelerate the transition away from reliance on fossil fuels.

Policy context: fossil fuel abundance

Figure 1 shows the overall trend in global consumption of fossil fuels, nuclear, wind and solar (also in the insert plot), hydro, biomass and waste (and other renewables) from 1972 to 2015, together with the required reduction in fossil fuel use to limit global warming to well below 2°C. This required reduction assumes: (1) a halving in global CO_2 emissions every decade from 2020[2] up to 2050 as suggested by Rockström et al. (2017); (2) emissions factors taken from the International Energy Agency (IEA, 2017a); and (3) that the ratio between coal, oil and gas is maintained at current levels (a change in ratio would only marginally change the shape of the curve).

From Figure 1, it can be concluded that, in spite of the strong growth in wind and solar since 2004 (insert plot), their shares of primary energy demand remain very low compared to fossil fuel use, and that both a highly disruptive reduction *in the use of fossil fuels* and increase *in investments in alternatives to fossil fuels* (in combinations of wind, solar, biomass, other renewables, hydro and nuclear) are required to approach near zero emissions around 2050. The required change (disruption) in phasing out fossil fuels could be somewhat less dramatic if CCS can be ramped up at large scale over the next decades (the emission reduction profile provided by Rockström et al., includes a certain ramp-up of BECCS and contribution from land-use change). However, considering that there are currently no large-scale CCS or BECCS projects in place, and the long lead times for large-scale implementation of these technologies, it is unlikely that these will provide a substantial contribution to emission reductions prior to 2050.

It is worth noting that, since Figure 1 uses primary energy data, it conceals conversion losses (e.g. from combustible sources to electricity or well-to-wheel in the road transportation systems) to final energy use supplied by oil, coal and gas (and biomass). On the other hand, wind and solar power require higher capacity to produce the same amount of energy as thermal generation, due to the much lower full-load hours of wind and solar power. Thus, the actual deployment of zero-GHG emission energy sources (wind and solar in particular) required to replace fossil fuels while matching supply and demand, cannot be deduced directly from Figure 1. This will ultimately depend on the development of final energy demand (including cogeneration of heat and other

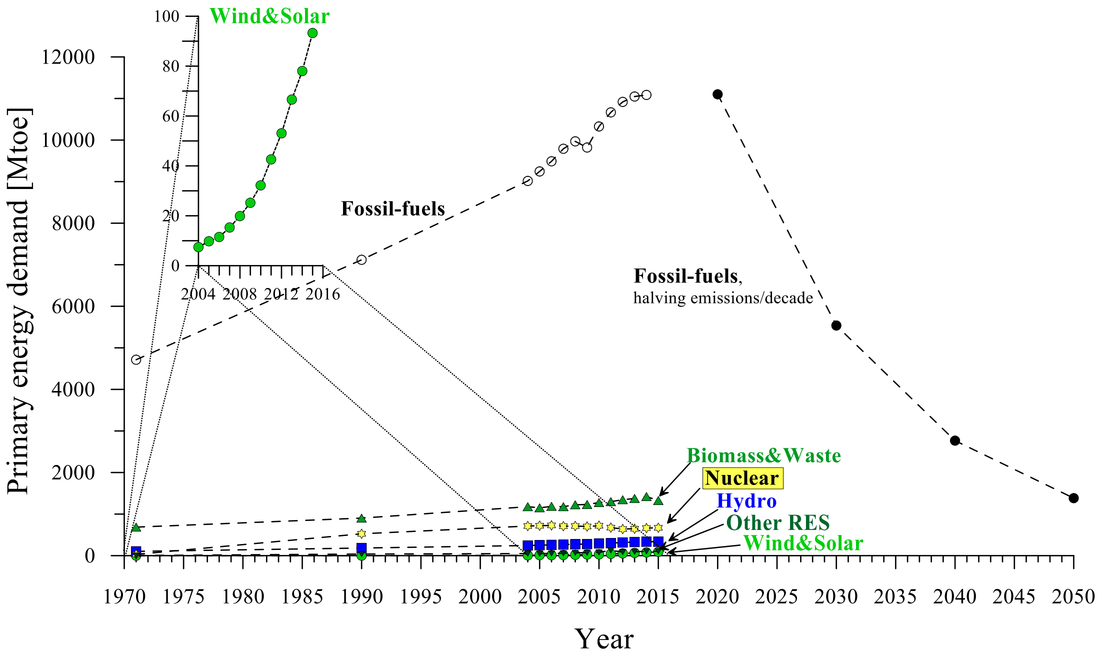

Figure 1. The development in primary energy demand from fossil fuels, wind and solar, other renewables, hydro and nuclear, from 1972 to 2015.

Notes: The filled symbols are approximations of the reduction in fossil fuel consumption required if halving the gross anthropogenic CO_2 emissions every decade in line with 'the Carbon Law' proposed by Rockström et al. (2017). The filled symbols assume that the ratio between coal, oil and gas is maintained at current levels while halving emissions from fossil fuel use every decade, not considering any offsetting by CCS. For wind, solar and hydro, the 'physical content method' is applied, i.e. their electricity output is taken at the point of generation of electricity, and their 'primary energy equivalent' is computed as the electricity generated in the plant (not assuming displaced thermal generation, which requires assuming a value for the thermal efficiency of the plant to compute the 'primary energy equivalent', i.e. the displaced thermal generation would then be the electricity generated from these plants divided by an assumed thermal efficiency).

energy carriers) and how the integration of wind and solar power is managed (e.g. degree of electrification and the amount of thermal power required to balance wind and solar). Nevertheless, it should be clear from Figure 1 that there must be a dramatic ramp-up of alternatives to fossil energy in order to comply with the emission reductions required to fulfil the Paris Agreement.

Figure 2 shows global investments in renewable energy sources (RES) since 2004, which is when expansion in renewables has been the strongest. The figure also includes the shares of fossil fuel and non-hydro renewable energy sources (NHRES) in global primary energy demand; together with Figure 1 it can be seen that fossil fuels still account for more than 80% of the global primary energy supply and that the large expansion of NHRES[3] has in fact, so far, not resulted in any reduction in the fossil fuel share of primary energy demand.

With respect to fossil fuel extraction, there are several works pointing to the fact that only part of the available *reserves* of fossil fuels can be extracted and burnt if the world is to comply with the above-mentioned warming target (e.g. Bauer et al., 2016; McCollum, Bauer, Calvin, Kitous, & Riahi, 2014; Steckel, Edenhofer, & Jakob, 2015). The emission potential of the aggregated global fossil fuel reserves is around 2860 Gt of CO_2 (BGR, 2016; IEA, 2017a), corresponding to around two to five times the remaining carbon budget, estimated to range between 590–1,240 Gt CO_2.[4] It should also be noted that fossil fuel *resources*[5] (coal resources in particular) are significantly greater than the reserves, although a large part of the resource base is characterized by high extraction costs. Based on the total fossil resource base at the end of 2015 as given by BGR (2016), the total emission potential (reserves plus resources) is around 47 000 Gt of CO_2 (BGR, 2016; IEA, 2017a).

Although it may seem self-evident that only a fraction of the available fossil fuels can be permitted to be used if severe warming of the planet is to be avoided (IEA, 2014a; McGlade & Ekins, 2015), the scientific literature contains little information on the implications of the abundance of fossil fuels on the possibilities for mitigating global warming in a geopolitical context. Pfeiffer and Mulder (2013) investigated the diffusion of NHRES technologies for electricity generation across 108 developing countries in the period 1980–2010, and they

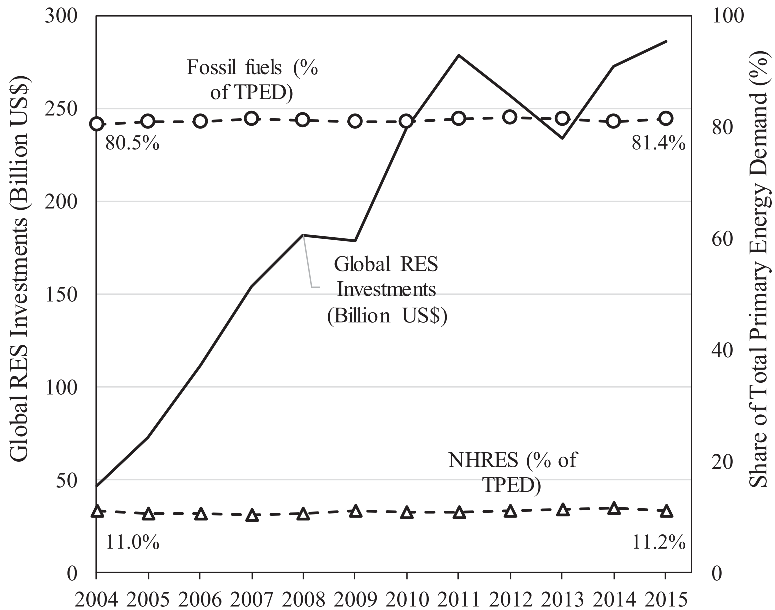

Figure 2. Comparison of the global trends in RES investments with the NHRES and fossil fuel shares in total primary energy demand (TPED). The RES investments include R&D and hydropower up to 50 MW (i.e. not large-scale hydro). From Frankfurt School/UNEP (2016, 2017), IEA World Energy Outlook 2006–2017 editions.

concluded that a high-level of fossil fuel production delayed the diffusion of NHRES technologies. Friedrichs and Inderwildi (2013) identify what they refer to as 'the carbon curse'. They conclude that fossil-fuel-rich countries have followed carbon-intensive development pathways (in terms of CO_2/gross domestic product (GDP)), clearly indicating the challenge of changing course in countries which have an intense use of fossil fuels (although their work covers data only up to year 2008). In a recent article, Spencer et al. (2017a) analyse the political economy and labour aspects of the fast phase-out of coal required to comply with a 1.5°C target, including a policy analysis of four major coal-using countries. They conclude that a policy framework that can transform the coal sector in line with a 1.5°C target remains a long way off. Also, the fact that the fossil fuel share in global energy supply has remained largely constant (~80%) for more than a decade (cf. Figure 2), in spite of rapid expansion of renewables, combined with the large reserves of fossil fuels, obviously imposes a great threat to climate change mitigation. Thus, there is a need to analyse trends in fossil fuel use and, based on the results from this, discuss policies directly targeting fossil fuel supply or fossil-fuel-based CO_2 emissions.

Methodology, data sources and statistics

The synthesis provided in this article is based on a relatively vast body of relevant literature and data sources. We use the data to explore trends in fossil fuel and NHRES consumption[6] using the indicator Megaton oil equivalents (Mtoe[7]) in order to be able to include all sectors (transport, industry, buildings and electricity) in the same indicator. We also relate the fossil fuel reserves to the GDP per capita (Mtoe/GDP/cap), to reflect the value of the fossil fuel reserves in the economy.[8]

We focus on 10 individual countries – Australia, Brazil, Canada, China, Germany, India, Japan, Russia, USA, Venezuela – and the EU and Middle East[9] as separate regions. Germany is reported separately from EU28 since there has been a particular strong expansion in RES-based energy in Germany, further accelerated by the 'Energiewende'. As indicated above, NHRES is herein defined as wind, solar, biomass and 'other renewables' but excluding hydropower, given the assumption of limited expansion of hydropower in *developed* regions (confirmed by the statistics for the period 1990–2010). Hydropower is instead reported separately, since in developing regions, especially

China, it has grown rapidly compared to USA and Europe, and this growth is expected to continue (IEA, 2015a, 2016a). The levels of domestic fossil fuel endowment are given as reserves (BGR, 2016).

Data on fuel mixes in primary energy demand are taken from various editions of IEA's World Energy Outlook (2006 to 2017 editions). Since these data are available up to year 2015, the main part of the results covers up to that year. Nevertheless, recent trends in 2016 are also cited when possible, using other statistics such as from BMWi (2017), GWEC (2016, 2017), REN21 (2016), Frankfurt School/UNEP (2016, 2017) and EWEA (2016). For Australia and Venezuela, data are taken from IEA Natural Gas Information (2015) and BP Annual Statistics (2015).

Fossil fuel reserves

Figure 3 compares the size of the domestic fossil fuel reserves (coal, oil, and gas) in absolute terms (Figure 3(a)) and as related to GDP/capita (Figure 3(b)) for the countries investigated. Although we have no strict definition of the difference between fossil-fuel-rich and fossil-fuel-lean countries, we use the fossil-fuel reserves related to GDP/capita (Figure 3(b)) to differentiate between these, with the division indicated in Figure 3(b). With this criterion, Australia, China, India, Middle East, Russia, USA and Venezuela have large reserves of fossil fuels. Together they are holding around 80% of the global fossil-fuel reserves. Although Australia has only marginally more fossil fuels than EU and Canada when relating to GDP per capita (Figure 3(b)), we chose to define it as fossil-fuel-rich since in absolute terms there are large amounts of fossil fuels (Figure 3(a)) and Australia is a major coal exporter.

Figure 3(a) shows that coal is the dominant fuel in the regions with large fossil reserves, except for the Middle East and Russia (in Russia, reserves of gas and hard coal are essentially equal). For the fossil-fuel-rich countries, the domestic fuels represent a very high value with large investments along their supply chain and associated with important local and regional social path dependency (job opportunities, workforce skills, knowledge etc.).

For the EU as a whole, Canada, Germany, Brazil and Japan, the picture is different, since they hold fewer or far fewer domestic fossil fuel reserves, with Germany having some lignite deposits and the EU having a mix of mainly natural gas and lignite. Brazil has some oil and lignite and Japan has hardly any fossil fuels at all, as well as not so favourable conditions for domestic RES-energy. Thus, the potential economic value of the fossil fuel reserves is much lower in these countries than for the above-mentioned fossil-fuel-rich regions (Figure 3(b)). Nevertheless, it should be emphasized that although the absolute value is modest, the value to local economies can be significant, as for instance in the eastern parts of Germany where large lignite reserves are located. Similarly, Poland, which has lignite and hard coal reserves, generates most of its electricity from coal.[10] Also Canada is often associated with fossil fuels as being an important part of the economy, but this

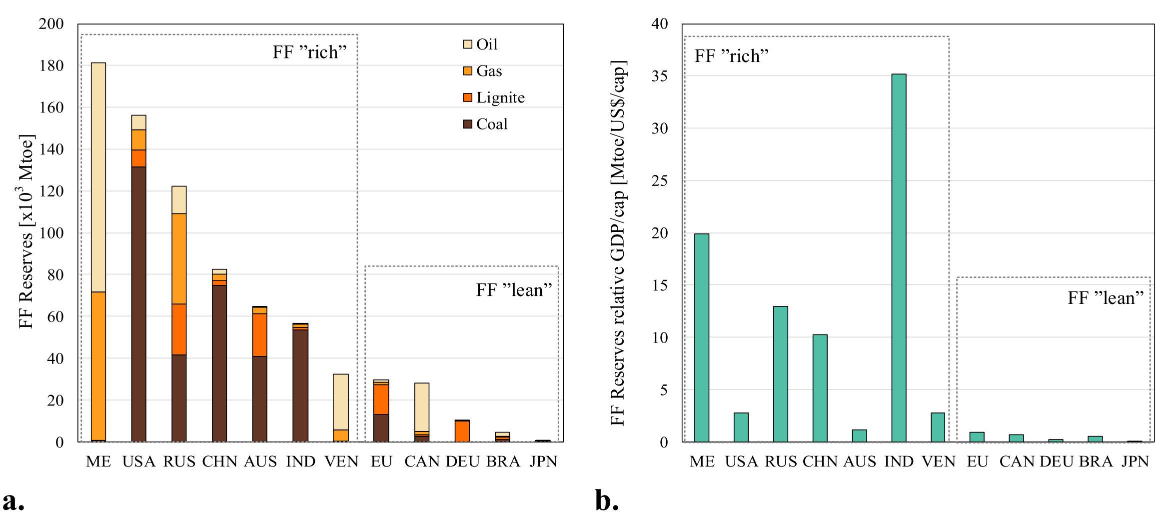

Figure 3. Comparison of (a) size of the reserves of fossil fuels (coal, oil and gas) and (b) the reserves related to GDP/capita for the regions investigated in this work. Reserves have been taken from BGR (2016).

is partly local and when relating to the GDP/capita for the entire country as in Figure 3(b), the fossil fuel reserves are on the level of those in EU. Canada's fossil fuel reserves are mainly in the form of oil.

Regional trends in use of fossil fuels and NHRES 2004–2015

Figure 4 compares the development in primary energy demand from fossil fuel and NHRES, for the fossil-fuel-rich countries (Figure 4(a,b)) with the development in the regions with little fossil fuels (Figure 4(c,d)) between 2004 and 2015 (figures shown are relative to 2004).

From Figure 4(a), it can be seen that there has been a steady increase in primary energy demand from fossil fuels in Middle East, China, India and Venezuela.[11] The growth in China stands out, both in absolute and in percentage terms, although the data show that the increase in fossil fuel consumption in China has levelled out over the last few years included in the statistics (2013–2015). However, recent data point to an increase in global CO_2 emissions in 2017, mainly due to increased emissions from carbon-intensive industries in China (GCP, 2017; IEA, 2018a). Primary consumption of NHRES in China has in fact declined by 10 between 2004

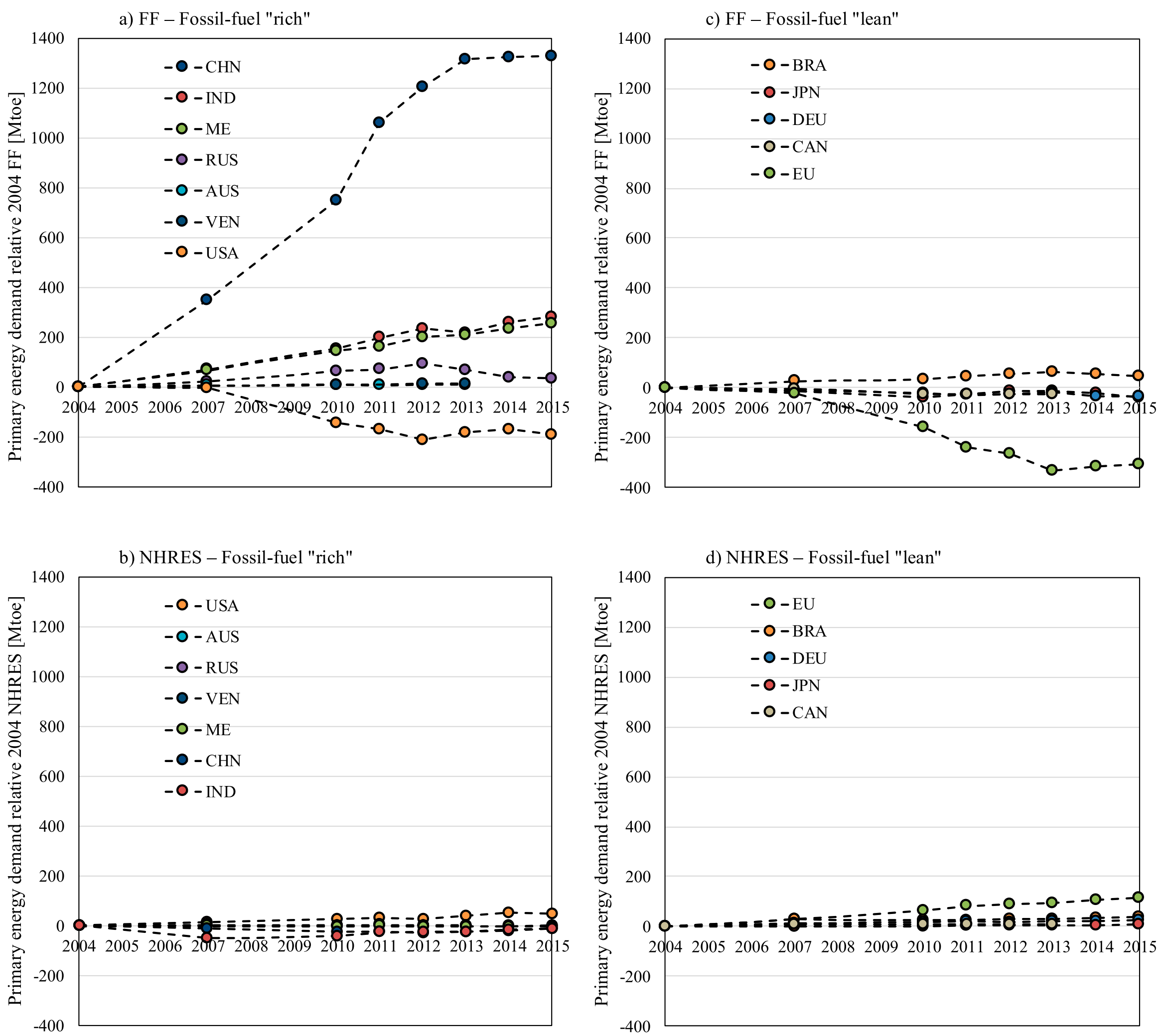

Figure 4. The development in primary energy demand from fossil fuels and NHRES for fossil-fuel-rich countries (a, b) and fossil-fuel-lean regions (c, d) over the period given in Figure 1. The data are plotted relative to 2004.

and 2015, due to revised figures for primary consumption of biomass (IEA, 2017b).[12] Due to the growth in fossil fuel consumption, the NHRES share decreased from 11% to 5%. The reason for the decrease in the share of NHRES in total energy demand is that the NHRES development has happened almost exclusively in the electricity sector, and to only a very limited extent in the industry and transportation sectors. In addition, wind power generation in China suffers from low full-load hours, around half those in the US (IEA, 2016a, 2017a).

India increased its primary fossil fuel consumption by 82% between 2004 and 2015 (cf. Figure 4(a)), while at the same time NHRES-based energy demand declined by 6% (the share declined from 37.5% to 23.6%). According to IEA (2015b), India was responsible for almost 10% of the increase in global primary energy demand between 2000 and 2013 (accounting for 18% of global population). In 2015 the Indian Government announced an aim to raise coal production from 600 Mt (in 2013) to 1500 Mt by 2020 (IEA, 2015b). Although such a significant increase appears optimistic, there is little doubt that coal demand in India will increase substantially in the future. In the Middle East, primary fossil fuel consumption has increased by 54% since 2004 while consumption of NHRES is virtually non-existent (declining from 2 Mtoe in 2004 to 1 Mtoe in 2015). In Russia, primary fossil fuel consumption has increased modestly by 6% while consumption of NHRES has stayed constant. The fossil fuel development in Russia reflects low economic growth, reaching a temporary post-Soviet-era peak in 2012, after which the fossil fuel consumption has declined and was down by 8% in 2015 (not directly seen in Figure 4 since data show fuel consumption relative to 2004). An exception from the trend of increased consumption of fossil fuels in the fossil-fuel-rich countries is the US. In the US, a shift from coal to natural gas and a 16% decline in oil consumption has resulted in a net reduction in fossil fuel use as can be seen from Figure 4(a). However, the share of fossil fuels in primary consumption remains high at 83%. As can be seen from Figure 4(a), both Australia[13] and Venezuela have experienced a growth in fossil fuel consumption between 2004 and 2013 (9% and 29%, respectively). Although Australia has doubled its NHRES consumption, NHRES still constituted less than 5% of primary consumption in 2013 while fossil fuel consumption accounted for almost 94% (cf. Figure 4(b)).

From Figure 4, it is clear that, for the fossil-fuel-rich countries that can be considered as developing or newly industrialized economies (China, India, Venezuela and Russia), and in the Middle East, the growth in primary

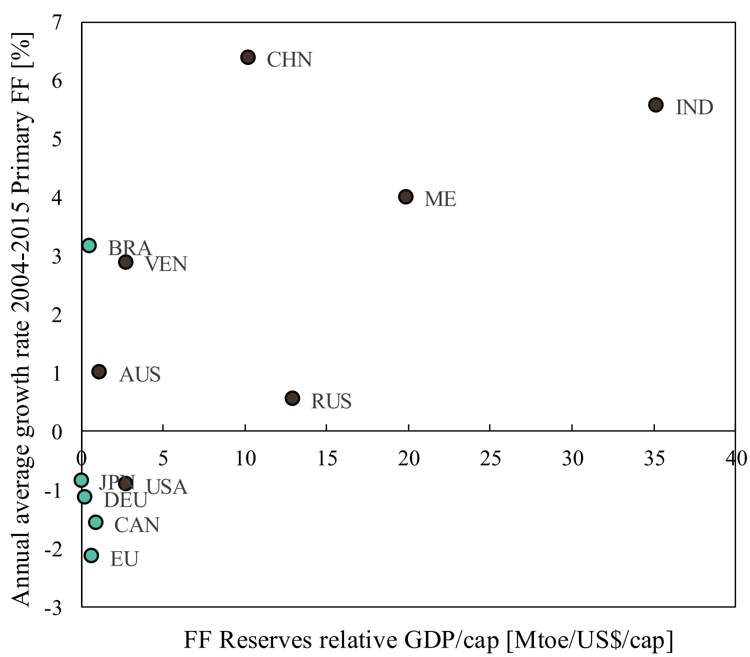

Figure 5. The compound average annual growth rate (CAAGR) in primary consumption of fossil fuels for the countries investigated in this work over the period 2004–2015.

energy demand from fossil fuels is far larger than from NHRES *in terms of growth in absolute numbers*. This is summarized in Figure 5, which gives the compound average annual growth rate (CAAGR) in fossil fuel consumption for all countries covered in the analysis, over the period 2004–2015, in relation to the fossil fuel reserves related to GDP/capita (PJ/USD). As can be seen, only fossil-fuel-lean countries have a reduction (negative growth rate) in their fossil fuel consumption. However, Brazil shows an increase in fossil fuel use, in spite of small fossil fuel reserves, but as can be seen from Figure 4(c), the increase is from low levels and, in addition, there is a decrease since 2013. Also, the above-mentioned exception, that US decreased its fossil fuel consumption despite large reserves, can be seen. In summary, the fossil-fuel-rich regions increased their primary consumption by 1737 Mtoe between 2004 and 2015, whereas the corresponding growth for NHRES was a mere 25 Mtoe.

Uncertainty in statistics

The official statistics used in this work are available up to 2015. It should be emphasized that compilation of global statistics always will be subject to some statistical uncertainty (see for example Korsbakken, Peters, & Andrew, 2016, on uncertainties in the actual coal use in China[14]). This is particularly the case for data from recent years. According to IEA (2015c, 2016b, 2017c), global emissions of CO_2 from the energy sector and from cement production stayed flat both in 2014 and 2015, while according to PBL/JRC (2015) global CO_2 emissions from fossil fuel combustion and industrial processes (production of cement clinker, metals and chemicals) *increased* by 0.5% in 2014. Furthermore, and as indicated above, the most recent data (GCP, 2017; IEA, 2018a) point to an increase in global CO_2 emissions in 2017. It does not, therefore, seem as if the conclusion by the IEA (2017c) that the growth in global CO_2 emissions was well below global economic growth both in 2014 and 2015 is sustainable in indicating a strong decoupling of economic growth and emissions. If the above-mentioned indications that emissions have regained growth in 2017 prove to be robust, the remaining carbon budget which complies with a 2°C warming target will soon be used up, and obviously even more so if targeting 1.5°C warming in line with the Paris Agreement.

Potential growth in energy demand from newly industrialized countries

Half the world primary energy demand is consumed within three regions which collectively comprise 30% of the world population: China, EU and US. Adding India, the group accounts for nearly 50% of global population and 56% of global primary energy demand. With economic growth, there is a large potential for increased energy use, particularly in India but also, to some extent, in China, since the per capita levels of energy use in these countries are still significantly lower than in the developed regions. For example, taking India's per capita primary energy demand with today's population up to EU levels would raise *global energy demand* by 25%. Likewise, bringing electricity generation in India to the same level as in the EU would raise global electricity generation by 30%. Obviously, these figures would increase even further if India's expected population growth was included, that is, from the current 1280 million to an expected 1600 million in 2040. This increase may, however, of course be somewhat counteracted by improved energy efficiency. China's consumption levels per capita are also well below corresponding levels in the EU, with per capita primary energy demand and electricity generation both around a third of the corresponding figures for the EU-28 in 2014. There is also a high energy growth potential in Africa, where per capita consumption levels are very low and where the total population is expected to double by 2050 to 2.4 billion (UN, 2017). The number of vehicles and passenger cars also signals a tremendous potential for growth in China and India. Considering 'all registered vehicles on the road', in 2013 there were 564 and 790 vehicles per thousand people in the EU and USA, respectively, but only 91 and 20 vehicles per thousand people in China and India (OICA, 2016).

The future development of carbon emissions in China and India and other potential high growth-rate countries obviously depends on many factors. Sanwal and Zheng (2018) conclude that China's future emissions will, to a considerable extent, depend on growth of transport and building-related services since these are strongly related to the well-being of the middle-class. Considering the above-mentioned high potential for increase in the vehicle density in China and India, it seems wise, as pointed out by Sanwal and Zheng (2018), to have a strategy that tries to ensure that the drivers of consumption differ from those of countries that urbanized earlier. In this respect, there are indications that China may have entered a new development regime compared to the period between 2000 and 2013, which was characterized by high growth of heavy industry (Green & Stern, 2016); this also seems to agree with Figure 4(a). China has stated, in its nationally determined contribution to the Paris Agreement, that it aims to peak GHG emissions in 2030 at the latest. As mentioned above, it is too early to conclude when China can divert continued economic growth from carbon-intensive consumption. It should also be mentioned that while, for obvious reasons, most attention is currently directed towards trends in countries such as China and India, increases in the use of fossil fuels in general, and coal in particular, in Southeast Asia and countries such as Pakistan and Bangladesh, where coal currently plays a small role but is on the rise, will have important implications for the global effort to control climate change.

Strategies and policies for countering fossil fuel abundance

Carbon pricing systems, green innovation and industrial policies aimed at fostering low-carbon energy technologies are typically seen as the backbone of national and international decarbonization efforts (Meckling, Sterner, & Wagner, 2017). However, unlocking the political constraints related to regional distribution of fossil fuel endowments and existing and planned fossil-based infrastructure will also require, to a much larger extent than today, strategies, policies and international agreements directly targeting the transition away from fossil fuels – especially in fossil-rich emerging economies. In this context, it is important to note that the Paris Agreement does not mention fossil fuels at all (and nor do the 1997 Kyoto Protocol, nor the United Nations Framework Convention on Climate Change (UNFCCC) itself). The nationally determined contributions (NDCs), that is, mitigation pledges, of the fossil-fuel-rich countries analysed in this article contain basically no strategies relating to future fossil fuel supply, a conclusion also reached by Piggot, Erickson, Lazarus, and van Asselt (2017).[15]

Table 1 summarizes potential strategies and policies directly targeting fossil fuels, including pricing fossil carbon emissions, and other strategies and policies that influence the fossil fuel supply (some of these are sometimes referred to as supply-side policies). There are obviously many initiatives and policies that promote the use of renewable energy and increased energy efficiency; these are not included in Table 1 since the argument of this article is that, although these are of great importance, they are not sufficient to ensure that the fossil fuels are left in the ground to the extent required (cf. Figure 4).

It is obvious that a 'sufficiently high' global carbon price would ultimately disincentivize the use of fossil fuels, and thus leave remaining fossil fuels reserves stranded, or else make it profitable to apply CCS. Such pricing could be in the form of an emission trading scheme (e.g. the EU-ETS) or a carbon tax, either on emissions or on the fuel (cf. Table 1). However, regulating carbon emissions through direct pricing is often politically challenging (Meckling et al., 2017). Trading schemes (e.g. EU-ETS) have so far failed to result in the transformative changes required (cf. Figure 2), and although there are attempts of such schemes also in regions and countries with large fossil fuel reserves (China, Australia, Canada and US of the fossil-fuel-rich regions investigated in this work), the carbon prices in these schemes are so far low (Métivier, Bultheel, & Postic, 2018) and it is too early to draw conclusions on their effect (see discussions on China's national emission trading system by Parenteau & Cao, 2016; Swartz, 2016; Wang, 2013).

Another way to discourage the use of fossil fuels would be the introduction of emission performance standards (EPS), applying limits stringent enough to prevent the use of certain fossil fuels, such as coal as fuel in power plants (cf. Table 1). For example, in 2015 both the US[16] and Canadian governments introduced EPS systems (EPA, 2015, SOR/DORS/2012-167) with carbon emission limits that make it impossible to build new coal-fired power plants without CCS. This, in effect, promotes a shift to coal power with at least partial CO_2 capture, highly efficient natural gas plants, or renewables. As can be seen from Figure 3(a), most of Canada's fossil fuel reserves are not in the form of coal but consists mainly of oil and, as seen from Figure 3(b), Canada represents a fossil-fuel-lean country if relating reserves to GDP/capita. In the US, low gas prices mean that new coal-fired power plants are not expected to be built. The impact of EPS on Canada and the US is therefore likely to be limited since coal power is unlikely to be competitive. A relevant question is what would be required for such EPS policy measures to be implemented in countries with large assets of coal and without access to domestic reserves of natural gas. Local air pollution, as is the case in China, may result in significantly

Table 1. A summary of potential policies directly targeting fossil fuels, some of which are already implemented, and others that may be implemented in future. 'Policies' are typically implemented by governments, whereas 'strategies' can be industry initiated on a voluntary basis.

Fossil fuel policy/strategy	Principle	Sector	Challenges
Carbon emissions pricing See, e.g. Baumol and Oates (1971); Ellerman and Buchner (2007); and Mecklinger et al. (2017), Parenteau and Cao (2016)	A trading system or a tax that typically targets large emission sources *Examples*: The EU-ETS, The Chinese National Trading System	Electricity[a] Industry[a]	Politically difficult to secure a sufficiently high price To create confidence in market participants (e.g. in monitoring, reporting, and verification)
Fossil fuel taxation See, e.g. Sterner (2007)	Pricing of carbon at the fuel level *Example:* The Swedish carbon tax on the transportation sector (taken out at fuel sale – petrol and diesel)	Transport[a]	Politically difficult to secure a sufficiently high price
Emissions performance standards (EPS) See, e.g. Fischer and Newell (2008); and Nyiwul, Shittu, and Dhanda (2015)	Setting a strict level of emissions per energy unit. *Examples*: EPS in grams CO_2/kWh of electricity generated and the current European EPS in grams CO_2/km of the passenger cars produced by the European car industries (EC, 2009; EU, 2011)	Electricity[a] Transport[a]	Difficult to set values that are sufficiently stringent unless there is a fossil alternative, i.e. an EPS ruling out coal-fired power can only be expected if there is an abundance of natural gas for power generation
Phasing out of fossil fuel subsidies See Coady et al. (2017); Rentschler and Bazilian (2016); and references therein	Removal of subsidies related to the supply and environmental costs and consumer taxes *Example*: Phasing out of regional support for airports	All	Lack of quantitative estimates of benefits from removing subsidies Political opposition to higher energy prices from public and industry groups
Divestments from fossil fuel industries See Ayling and Gunningham (2017)	To remove the fossil fuel share in stock portfolios *Example*: Pension funds reduce their share of ownership in fossil fuel-linked industries and increase investments in green bonds	All	Lack of customer engagement and a challenge to apply to fossil-fuel-rich countries (See Ayling & Gunningham, 2017; Green, 2018)
Procurement Rentschler and Bazilian (2016)	To use procurement of projects to promote carbon-lean projects *Example*: Procurement of road construction projects (e.g. Anthonissen, Van Troyen, Braet, & Van den bergh, 2015)	Buildings[a] Construction[a]	Lack of transparent tools for determining carbon intensity
Establishment of transition policies Spencer et al. (2017a); Porter (1998)	Various regimens for compensating for loss of business and income during the phasing out of fossil fuels and for establishing education directed towards transition economics *Examples*: Support for workers to find new jobs (see Spencer et al., 2017a). The so-called US '45Q' tax credit for storing CO_2 permanently underground, which will increase from USD 22 today (2018) to USD 50 in 2026	All	Lack of timing and co-ordination and too short-term
Targeting the fossil fuel supply See, e.g. Sovacool and Scarpaci (2016); and Vogt-Schilb and Hallegatte (2017)	Moratorium on new fossil capital (e.g. coal mines and coal plants) or the creation of compensation schemes, such as establishing a trust fund to strand fossil fuel assets (compensating nations/firms for leaving fossil fuels in the ground) *Example*: Yasuní-ITT Initiative in Ecuador to leave oil underground in exchange for financial contributions from the international community (Arsel & Angel, 2012) – an initiative that ultimately failed	All	Lack of funding, political pressure, lack of transparency in the process, and lack of trust in the real motivation behind the initiative (cf. Sovacool & Scarpaci, 2016; and Keyman, 2015)
Funding for research and demonstration projects	To support projects that are directly linked to reducing fossil fuel use or fossil-linked emissions to the atmosphere *Example*: Governmental support for research and demonstration of CCS	All	Unless combined with clear long-term carbon policy, likely to stall at the demonstration phase

(*Continued*)

Table 1. Continued.

Fossil fuel policy/strategy	Principle	Sector	Challenges
Collective action along value chains See Ostrom (2010); and Cole (2015)	To organize companies along the value chains to finance the development of CO_2-neutral products and services. Co-operation of industries along value chains from basic materials to end products and services. May involve governmental organizations. Example: The initiative 'Fossil-free Sweden', where different sectors gather to formulate targets toward becoming fossil-free, developing roadmaps to reach zero emissions	All	To devise a financial model to raise capital and to transfer the costs for investments in alternative fuels and technologies to end-consumers in a transparent way

[a]Indicates the typical sector in which the policy or strategy has been applied (several of the policies can be applied to all sectors).

stricter emission standards, but not necessarily on carbon emissions. It should be a challenge to impose strict EPS systems in countries such as China since the Chinese coal-fired power plants are relatively new with 70% of installed capacity less than 10 years of age and, thus, these cannot be expected to be closed soon. Chinese coal-based power generation capacity has doubled in less than 10 years, from 449 GW in 2006 to 900 GW in 2015 (IEA, 2008, 2017a). Assuming a power plant life time of 40 years, these additions alone will give rise to more than 120 Gt CO_2 (assuming 7500 hours of base load and 0.9 Mt CO_2/TWh_e). Thus, introduction of a strict EPS system in China – strict in the sense that it would in the near future not allow for coal-fired power generation unless combined with CCS – would turn a large fraction of coal-fired power plants into stranded assets or require massive installation of carbon capture on existing plants. The Chinese situation can be compared with only 5% of the installed coal-power capacity in the US being younger than 10 years, where such an EPS system would affect plants which have already reached their economic life time and, also, as mentioned above, coal power is under a phase out due to competition from gas. In the European transportation sector, an EPS system (EC, 2009; EU, 2011) has, however, made a difference in that it has put pressure on the vehicle manufacturing companies to reduce fuel consumption and develop alternative fuels. The EPS emission limit has been tightening over the years and the further reduction of the EPS emission limit may eventually lead to a shift to alternative fuels, including electrification which will influence EU petroleum imports from regions such as the Middle East.

Many economies rich in fossil fuels apply significant subsidies to these fuels, especially in the case of oil (IEA, 2018b; Victor, 2009). Coady, Parry, Sears, and Shang (2017) assessed the global energy subsidies, defined as the difference between what customers actually pay for the fuels to what they should be paying to cover supply costs, environmental costs and general consumption taxes, and found these to be 6.5% of global GDP, a value similar to that given by the IEA (2014b). It seems obvious that reformation and a gradual phasing out of fossil fuel subsidies are prerequisites for shifting away from the use of fossil fuels. Rentschler and Bazilian (2016) also point to the importance of removing fossil fuel subsidies together with applying various procurement processes favouring low-carbon energy.

Divestments from the fossil industry is another important emerging strategy which seems to be increasing among investors. According to Ayling and Gunningham (2017) divestments are mainly driven by public movement by means of political action and as influencing norms. As a result, there are already investors and companies who are actively divesting from the fossil fuel industry (e.g. foundations, universities, insurance companies, pension funds and holding companies), including those which take pro-active ways in only investing in sustainable assets. A purely rational argument for divestments in fossil fuel industry is the risk that future climate policy will devalue or make the fossil fuel reserves stranded assets (Ansar, Caldecott, & Tilbury, 2013). When it comes to larger divestment initiatives consisting of national and provincial governments, an example is the Powering Past Coal Alliance with the aim to phase out coal-fired power generation but which, as pointed out by Green (2018), is confined to jurisdictions with little fossil fuel infrastructure. There are several ways for social movements to try to reduce or ban the use of fossil fuels, as discussed by Piggot (2017). However, these movements seem so far not to have reached the countries with large assets of fossil fuels with the exception of the US, but which, as pointed out above, is reducing its carbon intensity for purely economic reasons mainly by replacing coal with natural gas. Although divestments from the fossil fuel industry seems to be increasing, Ansar et al. (2013) point to the fact that divested holdings are likely to find their way to neutral investors and they conclude that if divestments are to have a direct impact on the valuations of fossil fuel companies, they would have to emerge from changes in market norms or constrained debt markets.

Governmental funding to support projects and demonstration of technologies aimed at the fossil fuel sector should be an important part of a fossil fuel strategy. Funding of research and demonstration of CCS is of obvious importance for fossil-fuel-rich countries. Application of CCS would allow such countries to continue using part of their fossil fuel assets, while reducing fossil-fuel-related CO_2 emissions. However, as indicated in Table 1, it is not likely that there will be large-scale application of CCS without a sufficiently high price for CO_2 emissions.

Spencer, Berghmans, and Sartor (2017b) discuss transition policies for the coal sector and point to several ways to compensate for early retirement of coal sector assets in production as well as consumption. It is likely that the same will be required for the oil and gas sectors. A transition policy is a way to divert from the path dependency followed by the fossil fuel industry and its associated institutions. To be effective, a transition policy should involve a range of stakeholder institutions (e.g. universities, governmental agencies, think-tanks and trade associations); these could be organized as clusters to provide specialized support in the form of research, education and financial and legal services to support a transition to a renewable system (cf. Porter, 1998).

When it comes to coal-fired power generation, a transition policy should aim to avoid new builds, retire old plants and manage plant operations to support the massive entry of renewable electricity, which require the promoting of thermal power plants which can balance variations in non-dispatchable renewable electricity such as wind and solar power (Spencer et al., 2017b). Phasing out existing coal-fired power plants to the extent required by the 2 degree target (cf. Figure 1) will inevitably lead to significant amounts of stranded assets in China and other countries with new or planned coal-fired power plant fleets, such as India, depending on the requirements on return on investments (cf. Davis & Socolow, 2014; Pfeiffer, Millar, Hepburn, & Beinhocker, 2016). Caldecott, Sartor, and Spencer (2017) list the many factors that present economic and political challenges to the phasing out of coal: geographical concentration (resulting in strong regional economic dependency), identity (closing of coal mines not only based on economically rational arguments, but also social and cultural arguments), difficulty of achieving labour mobility and re-allocating human capital due to educational and skill limitations. It seems reasonable to believe that these factors are generally applicable to all fossil fuels. Similarly, Spencer et al. (2017a), point to the important role of potentially 'stranded regions' where workers, regional governments and the regional economy more broadly are dependent on the fossil fuel industry. They conclude that curbing coal demand at the rate required to live up to the Paris Agreement most likely requires the establishment of supply-side transition policies in such regions, e.g. the EU's Coal Regions in Transition Platform (EC, 2017). This includes fossil fuel export countries as discussed by Oei and Mendelevitch (2018) who – using Colombia as an example – point to the risk that maintaining or increasing mining volumes in such a country could lead to stranded investments and delay sustainable economic development.

In terms of avoiding new fossil fuel projects, a moratorium could be placed on investments in fossil fuel assets, which would become stranded if a strict emission reduction policy were to be implemented (see Vogt-Schilb & Hallegatte, 2017). However, the data shown in this article (trends in Figure 4) indicate that it does not seem likely that such a moratorium policy will be implemented in countries with large reserves of fossil fuels. The Yasuní-ITT Initiative in Ecuador stands out as a rare case where a country tried to raise funding to compensate for the financial loss that would be incurred by exploiting an oil field (Arsel & Angel, 2012). However, the initiative failed owing to several reasons, including lack of funding raised, political pressure for oil exploitation, lack of transparency in the process and lack of trust (see Sovacool and Scarpaci (2016); Keyman (2015)).

Piggot et al. (2017) suggest that countries could use the UNFCCC to develop policies to phase out fossil fuel supply in line with the Paris Agreement. It is difficult to see, however, how countries with large fossil fuel reserves (i.e. the ones investigated in this work) could be motivated to develop such policies, which, if strong enough, would, in effect, lead to the stranding of their fossil fuel assets (unless CCS is applied). These countries may also argue in terms of equity, i.e. for the right to benefit from using their resources as was historically done by developed countries (Piggot, 2017). Given that fossil fuel use in countries such as China and India (Figure

4(a)) is in part generated by goods produced for export to fossil-fuel-lean countries and regions (Figure 4(b)), emissions are, in effect, redistributed amongst nations (cf. Raupach et al., 2014). It thus seems important that fossil fuel supply policies involve importing consumer countries (e.g. EU as an importer of Chinese consumer goods). One option would be to establish requirements on the carbon footprint of imported goods, i.e. to include emissions embodied in imports for final consumption as discussed by Scott, Roelich, Owen, and Barrett (2018). This could be included in procurement criteria from big organizations and companies, or by means of carbon-related taxes on import goods. The latter would clearly have far-reaching implications in terms of the international trading system and its rules.

An important possibility from a policy point of view is that mitigating CO_2 emissions will have a small effect on the price of end products and services, at least when it comes to products derived from carbon-emission-intensive materials such as cement and steel (Rootzén & Johnsson, 2016a, 2016b, 2017). This should offer an important opportunity to develop new emission pricing systems of a 'green labelling' type, i.e. requiring that the cost to mitigate the CO_2 emissions can be transferred in a transparent way to the end-consumers. It is likely that an increased awareness among the public of the threat of climate change may result in that private consumers as well as various companies along value chains will be increasingly concerned about the carbon footprint of products and services. This should open up for new possibilities to price emissions to finance investments in CO_2 mitigation measures. Cooperation between different actors along the value chain in different business sectors (e.g. cement and steel to buildings and constructions) could be instrumental in accelerating the transition away from fossil fuels. This could constitute a form of collective action similar to what has been proposed by Ostrom (2010) who argues for polycentric efforts to reduce the risks associated with the emission of GHG and as means to obtaining benefits at multiple scales. In other words, a polycentric approach along value chains may offer an opportunity for accelerating decarbonization (cf. Cole, 2015 and references therein). Such collective action could be further enhanced by raising barriers to loans for carbon-intensive projects (e.g. for financing coal-fired power plants) including increased insurance costs for such projects.

Conclusion

We conclude that the abundance of fossil fuels imposes a great threat to climate change mitigation: The trends reported for the fossil-fuel-rich countries suggest it is not likely that these countries will impose a strict cap on emission or put a ban on the use of fossil fuels such as implementing strict emission performance standards on coal power plants unless there are clear demands from consumers for carbon-lean products and services. Limiting warming to 2°C or well below, will either turn domestic fossil reserves (and a large part of the existing up-, mid- and downstream infrastructure) into stranded assets, or require the rapid installation of an extensive CCS infrastructure, in most cases, from a non-existent base – a choice between Scylla and Charybdis[17] for energy policymakers. We conclude that it is of immense importance to make new efforts to develop policies and strategies that explicitly target the fossil fuels in fossil-fuel-rich countries, but which at the same time take into account the trade flow of products that typically occurs from the newly industrialized fossil-fuel-rich countries, to developed countries. Such policies must also include strategies for phasing out fossil-fuel subsidies and find a way to include fossil fuel policies in the NDCs of fossil-fuel-rich countries. Since international policies have to a large extent failed to reduce fossil fuel use so far, collective action along value chains in business to divert from fossil fuels – a polycentric approach – may be a way forward.

Notes

1. Considering the large annual volumes of CO_2 emissions, it is assumed that converting CO_2 to materials or energy carriers (so called carbon capture and utilization) can only marginally contribute to mitigating global warming. Carbon emissions from fossil fuels are related to the slow domain of the carbon cycle, where turnover times exceed 10,000 years, and thus, any measure to mitigate global warming must ensure that the fossil carbon stays in the ground over such time scales.
2. Year 2020 emissions have been set equal to Year 2015 emissions.
3. NHRES is the sum of wind, solar and biomass (and other renewable energy sources such as wave, tidal and geothermal energy). The reason that we distinguish technologies using NHRES is that continued expansion of renewable energy is expected to be primarily in energy from wind, solar and biomass technologies. Nuclear power may also contribute to replace fossil fuel use, especially in newly industrialized countries but nuclear is associated with long lead times and low acceptance in many parts of

the world. With respect to biomass it should be kept in mind that around half of its current use is in the form of 'traditional use', i.e. mainly inefficient burning for cooking in developing countries (IEA, 2017a).

4. With >66% probability of limiting warming to below 2°C; this budget is proposed by Rogelj et al. (2016) as the most appropriate (accounting for non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database). Limiting increase to 1.5°C would obviously reduce carbon budget even further.
5. Resources refer to the total amount of fossil fuel that exists. Reserves refer to the amount economically recoverable using current extraction technologies.
6. We use the notation 'consumption' when it comes to fuel use, including NHRES, but write 'energy demand', since energy cannot be consumed (or produced).
7. We use Mtoe since this is used by the IEA and other fuel-supply-related statistics although modelling studies often use EJ, where 1 Mtoe = 0.0419 EJ.
8. We do not make any analysis on fossil fuel rents, since such an analysis is complex and considered outside the scope of this article; rather this article provides a discussion on various factors influencing what make fossil-fuel-rich countries to continue develop their fossil fuel assets. For a discussion on fossil fuel rents, see Kartha and Davis (2016) who conclude that rents from fossil fuel production can constitute a significant proportion of the income of regions, especially in poorer regions.
9. Middle East includes Bahrain, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, UAE, Yemen.
10. Poland has also opposed the EU climate targets and refused to accept the Doha Amendment, which represents the second part of the pre-2020 Kyoto Protocol (Euractiv, 2017). This delayed the EU's acceptance of the Doha Amendment, although the EU eventually went ahead and joined without Poland.
11. For Venezuela data are only available up to 2013.
12. In fact, the decline in primary biomass consumption is much larger than the decline in NHRES according to the IEA (2017a, 2017b), from 173 Mtoe in 2004 to 114 Mtoe in 2015, i.e. by a third.
13. Data for both Australia and Venezuela are only available up to Year 2013.
14. In November 2015, the IEA published its 'Special data release with revisions for People's Republic of China' stating that previous published energy related data for the period 2000–2013 would have to be revised.
15. Chinas NDC states that total coal consumption should be controlled and that coal should be used efficiently.
16. The current US presidency has stated (4 April 2017) that it will 'suspend, revise or rescind' their EPS system.
17. Between Scylla and Charybdis is an idiom derived from Greek mythology, meaning 'having to choose between two evils'.

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