# Regional Distribution of Renewable Energy and the Abundance of Fossil Fuels

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**Abstract**

This paper discusses the extent to which technologies developed for the exploitation of renewable energy sources (RES) can be expected to substitute for fossil fuels, toward the goal of reducing usage of fossil fuels. We compare the changes in fuel mix for primary energy consumption and for electricity generation over the past decade between regions with large and small domestic fossil fuel resources. We conclude that for newly industrialized countries rich in domestic fossil fuels, there is only a moderate or no increase in primary energy from RES, coupled with significant increases in primary energy consumption from fossil fuels although recent but preliminary data show these trends to weaken. We use the notion of a "fossil fuel curse," which implies that it is not obvious that countries with large domestic fossil fuel resources will allow these assets to remain unexploited. This obviously imposes a tremendous threat to climate change mitigation leaving only two choices for fossil-rich economies: leave the fossil fuels in the ground and apply carbon capture technologies, both options calling for a sufficiently high cost to emit $CO_2$ or other policy intervention in order to take place.

**Keywords**

Fossil fuels • Domestic • Climate change • Renewable • Electricity • Fossil fuel curse

## 1 Introduction

State-of-the-art research indicates that reductions of 40–70 % in global GHG emissions ($CO_{2eq}$) are required until year 2050 to limit the global temperature increase to 2 °C with corresponding probabilities of 88–63 %[1] of exceeding 2 °C, with further reductions required after 2050 [1]. Limiting warming to 2 °C represents a significant challenge from both the technical and political aspects and the efficiency of applying such a target has even been questioned recently from a policy perspective [2].

In Europe and several other regions, the focus to mitigate climate change is put on the investment in renewable energy technologies, from both a policy (renewable subsidies) and a technical perspective (Research and Development). In the present work, we distinguish non-hydro-renewable energy (NHRES) technologies from hydropower. The rationale for this is that in developed regions, such as the EU and USA, expansion of renewable energy is expected to be primarily in energy from wind and solar technologies, given that there is limited potential to expand hydropower in these regions. While the past decade has seen a strong growth in hydropower in countries such as China and India [3], the continued diffusion of NHRES technologies is considered crucial for decarbonization of the energy system. An additional reason to separate NHRES is that in contrast to hydropower, the intermittent nature of NHRES-based electricity generation

[1]See Table 6.3, page 431, in IPCC (2014), Fifth assessment report, working group III, 2014 where combinations of $CO_2$ reductions and probabilities of exceeding 2 °C are given.

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requires balancing power. In fact, hydropower (with reservoir) can act as balancing power (although runoff hydropower will not provide this feature). Load following thermal generation and energy storage technologies can also compensate for variations in NHRES generation.

In recent decades, NHRES technologies, especially those that exploit wind and solar resources, have undergone rapid development around the world [4, 5]. Europe, in particular Germany, Spain, and Denmark, has successfully expanded wind power generation, thanks in large part to support schemes (such as feed-in tariff systems). Europe has seen a greater than fourfold increase in installed wind capacity over the last 10 years, with installations of 128 GW in the EU-28 being reached by the end of 2014 [6]. While Germany and Spain are leading the field of wind-generated electricity, with a combined output of 62 GW, there have also been rapid increases in wind generation capacity in other countries, in particular the countries bordering the North Sea [6]. There has also been a strong expansion of wind power in China, with 114.8 GW installed capacity reported at the end of 2014 [4]. In several countries, the expansion of wind power capacity has exceeded expansion in thermal electricity generation [3, 4, 6]. There has also been significant expansion of solar power, such that in 2014 the global cumulative Photo-Voltaic (PV) capacity was 177 GW [7]. Yet, in comparison with the consumption of fossil fuels, renewable energy use is still at a low level, and since fossil fuels remain abundant, their use is continuing and increasing in many regions. Fossil fuels still account for around 80 % of the global primary energy supply [3]. Thus, considering that the main reasons for expanding NHRES technologies are to mitigate $CO_2$ emissions and increase the security of supply, the question arises as to whether these technologies can be expected to reduce in a meaningful way the use of fossil fuels rather than promoting additional capacity or, together with fossil fuels, contribute to meeting increasing demand. Very little work in the scientific literature has to date addressed this question. Yet, various studies have investigated how the growth of an economy in a general sense relates to the level of domestic resources, with focus on developing countries. Thus, developing countries that are rich in oil or other natural resources have shown lower economic growth rates than those without these resources (this is of course for developing countries with low GDP and not for so-called newly industrial countries such as China and India). This phenomenon, which is known as the "Natural Resource Curse," has been identified from econometric tests of the determinants of economic performance across sample countries (see [8] and references therein). While different reasons have been suggested for the Natural Resource Curse [8, 9], some studies dispute its validity, arguing that natural resources do not dampen economic growth [9]. When it comes to the energy system, Pfeiffer and Mulder [10] conducted an investigation of the diffusion of NHRES technologies for electricity generation across 108 developing countries in the period 1980–2010, and they concluded that high-level fossil fuel production delayed the diffusion of NHRES technologies. Friedrichs and Inderwildi [11] identify what they refer to as "the carbon curse." Applying the carbon intensity ($CO_2$/GDP) they show that fossil fuel-rich countries have (up to year 2008) followed carbon intensive development pathways. Related to this, in a recent work Davis and Socolow [12] estimated the expected $CO_2$ emissions from committed power plants based on a data on trends in construction of fossil-fueled power plants and assumptions on expected operating lifetime (40 years). They come to the conclusion that total committed emissions from power plants are growing at a 4 % yearly rate and reached 307 Gt $CO_2$ in Year 2012 (although with a large uncertainty of several hundreds of Gt). A large portion of the fossil fuel plants being built worldwide are coal plants and many of these are built in newly industrialized countries such as China which has large resources of domestic fossil fuels, most notably coal. As an example, only in China coal-based power generation increased from 449 GW in 2006 to 791 GW in 2012. Thus, this gives an increase of 342 GW [3, 13]. Assuming a power plant lifetime of 40 years, these additions only will give rise to more than 100 Gt $CO_2$ (assuming 7500 h of base load and 1 Mt $CO_2$/TWh).

In summary, it appears that in developing and newly industrialized countries with large domestic sources of fossil fuels these assets will be used to support continued economic development. At the same time, there are currently only two options to mitigate $CO_2$ emissions from the use of fossil fuels; not using the fuels at all, i.e., leaving them in the ground; or applying Carbon Capture and Storage (CCS) technologies [14, 15]. To convert the $CO_2$ into useful energy carriers in a closed loop using a so-called Carbon Capture and Utilization (CCU) scheme (see [16, 17]) can hardly be an alternative of significant contribution to mitigating $CO_2$ emissions, considering the enormous amounts of $CO_2$ emitted (cf. [18] and references therein) and the fact that $CO_2$ is the most oxidized state of carbon, i.e., carbon in its lowest energy level. In a $CO_2$ constrained world, it seems unlikely that there will be an excess of renewable energy required to power CCU schemes, but there may be more cost-efficient use of such renewable energy for replacing fossil fuels.

## 2 Method

The values of domestic fossil fuel resources are related to the fuel mix for primary energy consumption and the technology mix for electricity generation. Countries and regions with large domestic resources of fossil fuels are compared with countries with low resources in terms of the increase in different fuels for primary energy consumption as well as the increases in fossil-based and NHRES-based electricity generation. 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). Yet, hydropower is reported separately, since in regions which have seen high economic growth, especially China, there has been strong growth in hydropower, and this is expected to continue [3]. The following regions are assessed: *China, EU-27, India, Japan, Norway, Russia*, and the *USA*. *Germany* is also assessed separately from EU27 since it is known for its large deployment of NHRES technologies in the form of wind and solar power. Most of the data are taken from the IEA [3, 12, 19–22], with additional data from other sources [23–25]. Since these official data are available up to the year 2012, the main part of the results covers up to the year 2012 (but with recent trends from 2012 to 2014 cited above, using other statistics such as from [4–6, 25].

The levels of domestic fossil fuels are given as reserves and reserves plus 30 % of the resource base [21, 24]. The resource base is defined by [24], considering several parameters such as carbon content and, with regard to coal, depth of deposit.

The arbitrarily chosen 30 % reflects the likelihood that part of the extensive resource base may also be used, which represents a significant threat to mitigating human-induced climate change [26]. Historically, there has been a continuous shift from the resource base to the reserves, mainly due to technological advances related to mining, oil and gas extraction, new discoveries, and increased prices. Thus, it is likely that this shift will continue and as stated elsewhere [14, 15], it is far from obvious that the abundant and consequently relatively low-priced fossil fuels will be left as stranded assets.

The economic values represented by the domestic fossil fuels are estimated by simply multiplying the reserves and resources by the current prices for coal, oil, and gas. Thus, this paper does not provide extensive analysis of resource economics, but rather focuses on the trends in domestic fossil fuels and gives an approximate assessment of the relationship to their economic value and the resources available. For the economic value of natural resources, the term "resource rent" (% of GDP) is sometimes used (e.g., [27]), which is defined as the difference between the value of the resource at a global market price and the total cost of production. As the derivation of such values is not straightforward, additional work outside the scope of the present paper is required for a detailed analysis of the economic value of the fossil fuel resources. The use of the fossil fuels obviously contributes to a large increase in BNP by means of the resulting goods and services created by burning these fuels. Thus, domestic fuel resources have the potential to generate increased GDP within the country or by means of exporting these fuels contribute to GDP increase elsewhere. There is a certain span in the way economies (countries) convert fossil fuel usage into wealth which can be seen from the GDP/carbon emitted which vary strongly across regions [28].

Regarding fossil fuel prices, these are taken from IEA [21] and the price for hard coal is based on the OECD steam coal import price in [23] for all countries. The price of lignite is set at the same level as hard coal (USD 123.4 per tonne coal equivalent) but is corrected for its lower heating value. For natural gas, the following import prices have been used: to Europe (for Russia, Germany, Norway, and the EU); and to Japan for China, India, and Japan. For the USA, the domestic US natural gas price has been used. The oil price is taken as the Crude Oil Import Price. The GDP values are from the World Bank [27].

The statistics of the fuel mixes in primary energy consumption and for electricity generation are taken from the IEA [3, 18, 21, 22, 29], with additional data for German electricity generation from [30–32] and the 2004 values applied to the EU-27 which have been taken from [33].

## 3 Results and Discussion

Table 1 lists the size of the reserves and resource base as well as the economic values of the domestic fossil fuels (coal, oil, and gas) for the regions investigated in the present work. It is clear that China, India, Norway, Russia, and the USA have large domestic resources of fossil fuels, with associated high economic values. Coal is the dominant fuel, with the exception of Norway, which has most of its domestic fossil resources in the form of natural gas and oil and where most of the economic value is realized through export. The economic value for 1 year of production (Year 2011) ranges from 3.3 to 35 % of the GDP for China, India, Norway, Russia, and the USA, i.e., the countries which can be considered to have large resources in fossil fuels. While the 35 % value clearly represents a large proportion of GDP, the 3.3 % of GDP value can also be considered to be significant given that it is for a "single" industry (the fossil fuel industry) and that burning these fuels in the domestic production system creates significant growth. The economic values of the reserves plus 30 % of the resources for China, India, and Russia are 33, 10, and 95 times the GDP, respectively. Thus, for these regions, the domestic fuels represent a very high value. Overall, it is clear that the large reserves and resources represent important economic assets for these countries.

For Germany and the EU as a whole, the picture is somewhat different, in that they have much less domestic resources of fossil fuels, with Germany having some lignite

**Table 1** Levels of reserves and resources of domestic fossil fuels for the regions investigated in this work, together with estimates of the corresponding economic values and their relationships to GDP

| Fossil fuels (Coal, oil and gas) | Energy content (EJ) | | Economic value (billion USD) | | | Economic value as % of GDP | |
|---|---|---|---|---|---|---|---|
| | Reserves | Reserves +30 % of resources | Reserves | Reserves +30 % of resources | 2011 production | 2011 production | Reserves +30 % of resources |
| **China** | **5254** | **48,627** | **26,164** | **239,058** | **643** | **8.8** | **3300** |
| EU27 | 1066 | 5784 | 5935 | 28,651 | 156 | 1.2 | 220 |
| Germany | 372 | 1185 | 1683 | 5366 | 14.8 | 0.4 | 150 |
| **India** | **2584** | **4462** | **10,821** | **19,144** | **131** | **7.0** | **1020** |
| Japan | 10.2 | 120 | 59 | 578 | 2.6 | 0.04 | 9.8 |
| **Norway** | **118** | **194** | **1410** | **2350** | **110** | **22** | **480** |
| **Russia** | **5622** | **36,629** | **39,322** | **179,993** | **658** | **35** | **9500** |
| **US** | **7384** | **70,056** | **34,634** | **309,981** | **494** | **3.3** | **2100** |

Fossil fuel-rich countries in bold

deposits and the EU having a mix of mainly natural gas and lignite (and some hard coal which since several decades are not profitable to extract). For Germany and the EU, the economic value of the fossil fuels is significant but much lower than those for China, India, Norway, Russia, and the USA. Japan has almost no indigenous fossil fuel resources (except for a limited amount of gas) and it is highly dependent upon fuel imports.

Table 2 shows the primary energy consumption levels, excluding nuclear energy, divided into fossil fuels, NHRES, and hydro, together with the trends observed in the period 2004–2012 for the countries investigated in the present study (see above). Since there have been indications that the growth in global $CO_2$ emissions has levelled off in 2014, the yearly trends 2010–2011 and 2011–2012 are included in order to see whether there was an indication of a slowing down in growth in fuel use between these years. For years 2013 and 2014, there are at the time of writing this paper (spring 2015) not yet any official statistics on the use of fossil fuels.

In China and India, there are large increases in the consumption of fossil energy over the last decade (2004–2012) with increase of 1205 Mtoe and 234 Mtoe for China and India, respectively, whereas there are only a slight increase in the total primary consumption from NHRES (in absolute terms). Yet, as can be seen from comparing the two right-most columns in Table 2, the growth in the Chinese fossil fuel use was lower in 2012 than in 2011. In India, the growth in use of fossil fuels was similar over the last two years investigated and also higher than the average over the last decade (2004–2012). Thus, up to year 2012 there was no sign in India of a slowdown in the use of fossil fuel.

The reason for the varying amount of NHRES in India is not known (increase from 1990 to 2004, followed by a decrease in 2010 and then again an increase in 2012). The well-known strong growth in wind power in China (see below) is not really seen more than that there is an enhanced increase in NHRES the last years (2011 and 2012) reported, while primary consumption from NHRES remained more or less constant from 2004 to 2010. The increase in wind power may also have been counterbalanced by the fact that there was a decrease in burning of biomass and waste from 2004 to 2010 (although the statistics may be associated with some uncertainties when it comes to small-scale biomass burning). Nevertheless, there has been a large (>40 Mtoe) increase in hydropower in China over the last decade (and a slight corresponding increase in India, although values fluctuate between years). The situation in Russia is similar, although there has been weaker growth in fossil fuels (due to lower economic growth). The level of fossil fuel use is, however, lower than in 1990 (which would represent “Soviet-era” conditions). For the EU-27, there has been a reduction in primary consumption of fossil fuels and an increase in NHRES. This is as expected, considering the ambitious targets for RES and GHG emission reductions of the EU, although NHRES still represents only about one-tenth of fossil fuel consumption (cf. Table 1). As shown in Table 2, the decrease in fossil fuel supply was less pronounced during 2012 than in 2011. Yet, the increase in NHRES is continuing and the yearly growth in 2012 was higher than the average yearly growth from 2004 to 2012. For some reasons, the NHRES growth in 2011 was only around half of the average growth in the period 2004 to 2012.

Germany shows a somewhat more pronounced reduction in the primary consumption of fossil fuels, as well as significant expansion of NHRES. Thus, for Germany, NHRES technologies can be considered to have substituted fossil fuel technologies. However, the use of domestic lignite in Germany has remained constant since year 2000 (1550 PJ in 2000, and 1572 PJ in 2014). For the regions compared, and

**Table 2** Primary energy consumption [Mtoe] from fossil fuels, NHRES, and hydro

| Primary energy consumption [Mtoe] | 1990 | **2004** | 2010 | 2011 | **2012** | Δ (2004–2012) | Δ/year (2004–2012) | Δ/year (2010–2011) | Δ/year (2011–2012) |
|---|---|---|---|---|---|---|---|---|---|
| *China* | | | | | | | | | |
| Fossil fuels | 670 | **1362** | 2114 | 2423 | **2567** | 1205 | 133.3 | 309 | 144 |
| NHRES | 200 | **221** | 222 | 238 | **242** | 21 | 2.3 | 16 | 4 |
| Hydro | 11 | **30** | 62 | 60 | **74.2** | 44.2 | 4.9 | −2.0 | 14.2 |
| *EU* | | | | | | | | | |
| Fossil fuels | 1351 | **1433***  | 1291 | 1239 | **1213** | −220* | −24.4 | −52 | −26 |
| NHRES | 49.0 | **81.5*** | 152.0 | 156.7 | **169.3** | 87.8* | 9.8 | 4.7 | 12.6 |
| Hydro | 25.0 | **26.3*** | 31.0 | 26.8 | **28.8** | 2.5* | 0.3 | −4.2 | 2 |
| *Germany* | | | | | | | | | |
| Fossil fuels | 305.0 | **285.9** | 258.1 | 248.9 | – | −37.0 | −4.6 | −9.2 | – |
| NHRES | 4.8 | **15.0** | 34.6 | 33.6 | – | 18.6 | 2.3 | −1.0 | – |
| Hydro | 1.5 | **1.7** | 1.8 | 1.5 | – | −0.2 | 0 | −0.3 | – |
| *India* | | | | | | | | | |
| Fossil fuels | 175.0 | **346.0** | 502.0 | 542.8 | **580.4** | 234.4 | 26.0 | 40.8 | 37.6 |
| NHRES | 133.0 | **214.0** | 172.0 | 187.2 | **188.0** | −26.0 | −2.9 | 15.2 | 0.8 |
| Hydro | 6.0 | **7.0** | 10.0 | 11.2 | **10.8** | 3.8 | 0.4 | 1.2 | −0.4 |
| *Japan* | | | | | | | | | |
| Fossil fuels | 371.0 | **441.0** | 404.0 | 413.7 | **427.7** | −13.3 | −1.5 | 9.7 | 14.0 |
| NHRES | 8.0 | **10.0** | 11.0 | 14.1 | **14.0** | 4.0 | 0.4 | 3.1 | −0.1 |
| Hydro | 8.0 | **8.0** | 7.0 | 7.2 | **6.5** | −1.5 | −0.2 | 0.2 | – |
| *Norway* | | | | | | | | | |
| Fossil fuels | 10.9 | **14.2** | 15.0 | – | – | 0.8 | 0.1 | – | – |
| NHRES | 1.1 | **1.4** | 1.5 | – | – | 0.1 | 0 | – | – |
| Hydro | 10.4 | **12.0** | 10.9 | – | – | −1.1 | −0.1 | – | – |
| *Russia* | | | | | | | | | |
| Fossil fuels | 822.0 | **579.0** | 643.0 | 650.6 | **672.5** | 93.5 | 10.4 | 7.6 | 21.9 |
| NHRES | 12 | **7.0** | 7.0 | 7.1 | **7.4** | 0.4 | 0 | 0.1 | 0.3 |
| Hydro | 14 | **15** | 14 | 14.3 | **14.3** | −0.7 | −0.1 | 0.3 | 0.0 |
| *US* | | | | | | | | | |
| Fossil fuels | 1655 | **2006** | 1864 | 1834.5 | **1792** | −214 | −23.8 | −29.5 | −42.5 |
| NHRES | 76.0 | **82.0** | 108.0 | 112.5 | **111.8** | 29.8 | 3.3 | 4.5 | −0.7 |
| Hydro | 23.0 | **23.0** | 23.0 | 27.7 | **24.0** | 1.0 | 0.1 | 4.7 | −3.7 |

*Values shown are for 2003, taken from [33]

in second place to Japan, Germany has the lowest domestic resources of fossil fuels. In Japan, which has almost no domestic fossil fuel resources (cf. Table 1), there has been a significant decrease in the use of fossil fuels over the period 2000–2011, although with a substantial increase from 2010 to 2012. Yet, there has been little increase in NHRES and hydro in Japan. This pattern in Japan is mainly due to energy conservation measures and weak economic growth. The status of nuclear power in Japan has obviously changed following the earthquake in 2011, and this is the reason behind the recent increase in use of fossil fuels. There is also a rapid increase in NHRES, especially from distributed solar photovoltaic (PV) panels (installed on rooftops). Norway has significant domestic resources of fossil fuels, although a major part of its production (83 %) is exported, while its electricity is almost entirely produced by hydropower. Overall, while there have been only moderate changes in the primary energy consumption in Norway over the period 2000–2011 (Table 2), there has been a significant increase in the use of fossil fuels as a consequence of increased demand from industry and transport. The overall small use of fossil fuels in Norway is obviously due to that the electricity system is almost 100 % RES based (hydropower).

Finally, it can be concluded that the USA is an exception in that it combines very large domestic resources of fossil fuels with a significant reduction in the primary consumption of fossil fuels in terms of Mtoe (Table 2). This is mainly due to energy conservation measures, a shift from coal to gas in

**Table 3** Electricity generation [TWh] from NHRES technologies, hydro, and fossil fuels

| Electricity generation [TWh] | 1990 | 2004 | 2010 | 2011 | 2012 | Δ (2004–2012) | Δ/year (2004–2012) | Δ 2011 | Δ 2012 |
|---|---|---|---|---|---|---|---|---|---|
| *China* | | | | | | | | | |
| Fossil fuels | 523 | 1830 | 3393 | 3854 | 3916 | 2086 | 232 | 461 | 62.0 |
| NHRES | 0 | 2 | 57 | 115.3 | 147.2 | 145.2 | 16.1 | 58.3 | 31.9 |
| Hydro | 127 | 354 | 722 | 699 | 862.8 | 508.8 | 56.5 | −23 | 163.8 |
| *EU* | | | | | | | | | |
| Fossil fuels | 1462 | 1776* | 1706 | 1654 | 1589 | −187* | −20.8 | −52.0 | −65 |
| NHRES | 25.0 | 133* | 321 | 384.5 | 452.9 | 319.9* | 35.5 | 63.5 | 68.4 |
| Hydro | 286 | 357* | 366 | 311.2 | 335.1 | −21.9* | −2.4 | −54.8 | 23.9 |
| *Germany* | | | | | | | | | |
| Fossil fuels | 372.4 | 385.1 | 368.8 | 362.0 | 361.1 | −24.0 | −2.7 | −6.8 | −0.9 |
| NHRES | 4.9 | 43.0 | 92.7 | 115.1 | 121.7 | 92.6 | 10.3 | 22.4 | 6.6 |
| Hydro | 17.5 | 19.6 | 20.5 | 17.5 | 27.9 | −8.3 | −0.9 | −3.0 | 10.4 |
| *India* | | | | | | | | | |
| Fossil fuels | 212.0 | 560.0 | 797.0 | 835.7 | 956.3 | 396.3 | 44.0 | 38.7 | 120.6 |
| NHRES | 0 | 6.0 | 22.0 | 52.7 | 50.9 | 44.9 | 5.0 | 30.7 | −1.8 |
| Hydro | 72.0 | 85.0 | 114.0 | 130.7 | 125.8 | 40.8 | 4.5 | 16.7 | −4.9 |
| *Japan* | | | | | | | | | |
| Fossil fuels | 532.0 | 671.0 | 706.0 | 808.4 | 881.7 | 210.7 | 23.4 | 102.4 | 73.3 |
| NHRES | 13.0 | 23.0 | 34.0 | 49.3 | 53.0 | 30.0 | 3.3 | 15.3 | 3.7 |
| Hydro | 89.0 | 94.0 | 82.0 | 83.2 | 75.5 | −18.5 | 2.1 | 1.2 | −7.7 |
| *Norway*** | | | | | | | | | |
| Fossil fuels | 0.1 | 0.4 | 4.4 | – | – | 4.0 | 0.6 | – | – |
| NHRES | 0.4 | 0.3 | 1.3 | – | – | 1.0 | 0.2 | – | – |
| Hydro | 121.1 | 138.9 | 126.3 | – | – | −12.6*** | 1.8 | – | – |
| *Russia* | | | | | | | | | |
| Fossil fuels | 798.0 | 604.0 | 696.0 | 710.9 | 722.4 | 118.4 | 13.2 | 14.9 | 11.5 |
| NHRES | 0 | 2.0 | 4.0 | 3.3 | 3.5 | 1.5 | 0.2 | −0.7 | 0.2 |
| Hydro | 166 | 176 | 166 | 165.8 | 165.9 | −10.1 | 1.1 | −0.2 | 0.1 |
| *US* | | | | | | | | | |
| Fossil fuels | 2213 | 2961 | 3060 | 2961 | 2941 | −20.0 | −2.2 | −99.0 | −20.0 |
| NHRES | 106 | 102 | 192 | 222.4 | 249.0 | 147.0 | 16.3 | 30.4 | 26.6 |
| Hydro | 273 | 271 | 262 | 321.7 | 278.5 | 7.5 | 0.8 | 59.7 | −43.2 |

*Values for 2004 are taken from [33]
**“2004 and 2010” values are from 2000 and 2009 [20], no values available for 2011 and 2012
***Variations in Norway are partly due to differences from precipitation, i.e., inflow to hydropower, rather than related to investments in or decommissioning of generation capacity

combination with increased use of NHRES and a slight increase in nuclear power, together with relatively weak economic growth. The increase in NHRES is moderate owing to the significant increase in domestic shale gas production, replacing coal in the power generation sector. Yet, it should be noted that the production of coal only decreased marginally (between 2009 and 2014, there was a 7 % decrease, from 975 to 907 Mt) whereas export increased by 64 % (from 54 to 88 Mt); [28].

Table 3 focuses on the electricity generation sectors in the same regions. From the values shown, it can be concluded that for regions that are rich in fossil fuels, the share of electricity generated from NHRES is in the order of a few percentage points. Of the total electricity generation (i.e., including nuclear), the fraction of NHRES is as follows (year 2012): China, 2.9 %; India, 4.4 %; Norway, 1 % (year 2009); Russia, 0.3 %, and USA, 5.8 %. However, China and India, as well as the EU and Germany, have seen strong growth in NHRES-based electricity generation in the period 2004–2012. For China, the growth in coal was also much less in 2012 (Δ2012) than in 2011 (Δ2011), a trend which seems to continue (based on various recent market indications). Yet, the expansion in NHRES also slowed down from 2011 to 2012 which may be interpreted as part of the slowdown is from a slowdown in economic growth rather than from a replacement with NHRES and other measures such as energy savings. In India, on the contrary, the increase in fossil fuel use was much higher in 2012 than the year before: a 121 TWh increase in 2012 compared to 39 TWh in 2011. The increase is mainly from an increase in the use of coal. As for NHRES the increase seen up to 2011 has completely stalled with no increase in 2012 (even a small decrease which may be due to inaccurate statistics).

For the USA, the 5.8 % share of electricity generated from NHRES has been established over a longer time period, mainly in order to increase the security of supply. It is clear that although there has been a large increase in NHRES use in the USA from 2004–2012, the level in 1990 was higher than that in the other countries. This, since a substantial fraction of the NHRES in the USA was installed as a response to the oil crises in the 1970s. Norway has a low level of NHRES, since Norway has almost all its electricity generated from hydro. The close to 100 % renewable source Norwegian electricity generation system was established in large part before Norway became a fossil fuel-producing and fuel-exporting country and is of course due to the favorable conditions for hydropower rather than an effect of a strong environmental policy (although there is a high carbon tax on domestic use of fossil fuels, i.e., mainly affecting the transportation sector). During the last decade, there has also been an off-shore carbon tax which has initiated capture of $CO_2$ from natural gas rich in $CO_2$ in order to make the natural gas marketable.

From Table 3, it is obvious that for the fossil-rich countries (cf. Table 1) that can be considered as developing/newly industrialized economies (China, India, and Russia), the growth in fossil fuel-based electricity generation is much larger than the growth in NHRES generation in terms of growth in absolute numbers, as given in the present work (TWh). Even in Norway, the growth in fossil fuel-based generation is larger than the growth in NHRES generation (albeit in both cases, the values are low and are also influenced by variation in precipitation, i.e., wet year and dry year compared with normal year influences on the amount of hydropower). It is only in the USA that there has been a growth in generation from NHRES similar to the growth in generation from fossil fuels, despite the fact that the USA has large fossil fuel resources. In fact, during 2010–2012, electricity generation from fossil fuels decreased, whereas NHRES grew. This is, as indicated above, mainly due to that there was a significant decrease in coal-based generation (with 350.6 TWh) to a large extent counterbalanced by a 246 TWh growth in natural gas generation. Thus, compared to year 2011, in which there was only little increase in the use of natural gas, the effect of the shale gas "revolution" seems to have been initiated during 2012.

For the EU including Germany, i.e., regions with low levels of fossil fuels, the growth in electricity generation from NHRES is significantly higher than that from fossil fuels. In fact, as evident from Table 2, there was a reduction in fossil generation in the EU, as well as in Germany, in the period 2004–2012. In particular, Germany has started to transform its energy system according to the Energiewende (Energy Transition) strategy, which targets the electricity generation system based almost entirely on the adoption of renewable sources. Yet, recent reduction in the price of hard coal has resulted in an increase in electricity generation from this fuel [25]. It is not clear what will happen with the German lignite-fired power plants considering the slowdown in CCS development. If $CO_2$ emission reduction targets are to be met, the domestic lignite resources have to be transformed into stranded assets at some point in the near future or lignite-fired plants will have to be equipped with CCS technologies. However, economic incentives for developing and implementing CCS are currently poor and public acceptance of CCS appears to be at a low level in Germany, especially with respect to CCS schemes that involve on-shore storage of $CO_2$ (as opposed to the more costly option of off-shore storage).

In spite of the fact that Japan has the lowest resources of domestic fossil fuels of the regions investigated, fossil fuel-based generation has increased approximately fivefold compared to NHRES during the period 2004–2011. Thus, dependence on fuel imports has increased steadily in Japan. The increase in fossil fuel for electricity generation was much higher in 2011 and 2012 than the yearly average over the period 2004–2012 which is an effect from the sudden reduction in nuclear generation following the earthquake in 2011. It seems likely that Japan will put more effort into developing NHRES technologies and energy conservation measures that match the Japanese infrastructure, which on the other hand will create challenges for the energy grid and capabilities for balancing intermittent electricity generation.

For China, India, and Russia, all of which have large domestic fossil fuel resources and significant levels of economic development, primary energy consumption and electricity generation from fossil fuels have increased at far higher rates than NHRES generation. In fact, considering the primary energy consumption levels of these countries, the increase in consumption from NHRES was only marginal over the period from 2004 to 2012 (there was a significant decrease in India and only a slight increase in China). The positive sign is that electricity generation from NHRES is substantial in China during the last two years investigated, and in 2012 the increase in electricity generation from NHRES was of the same order as the fossil electricity generation. Predictions [3] point to that the use of coal will peak in 2016 and that there will be a continued strong increase in NHRES, especially wind and solar.

For China, India, and Russia, we conclude that the evidence points to a great challenge to substitute renewable energy sources for fossil fuels, since leaving the fossil fuels in the ground will represent significant "stranded assets." In corollary with the expression "Natural resource curse" and similar to the "carbon curse" proposed by Friedrichs and Inderwildi [11], we propose a "fossil fuel curse," which implies that countries with large resources of fossil fuels cannot be expected to allow these resources to become stranded assets. Thus, this represents a significant threat to the mitigation of human-induced global warming.

In year 2014, global emissions of $CO_2$ from energy sector and cement production levelled out from a more or less constant steep growth since the late 1990s. To what extent his deviation is from a slowdown in economic growth or a true decoupling of economic growth and emissions is too early to say. It is clear that if emissions will regain a trend of strong growth the remaining carbon budget which complies with a 2 °C warming target would soon be used up. According to Friedlingstein et al. [34], the carbon budget would be used up in 30 years (from Year 2014) if emissions continue at Year 2014 rate. The main threat for the global community to comply with any reasonable warming target is the abundance of fossil fuels which so far has maintained and increased the momentum in construction of fossil-fueled processes: especially coal-fired power plants in newly industrialized countries such as China. It was recently shown that committed emissions in existing coal-fired power plants represent 50 % of the remaining quota under the assumption of a 50 % chance to stay below 2 °C if carbon, capture and storage is not applied [35].

## 4 Conclusions

We have compared the changes in fuel mix for primary energy consumption and for electricity generation over the past decade between regions with large and small domestic fossil fuel resources. We conclude that while the investigated developing regions show modest or no increases in primary energy from RES, they show large increases in primary energy consumption from fossil fuels. In the USA, fossil fuel consumption has declined over the last decade despite the presence of significant fossil fuel resources. The USA has also seen a significant contribution from increased energy conservation originating from a initial high carbon intensity.

We identify a possible "fossil fuel curse," which implies that countries with large domestic resources of fossil fuels cannot be expected to restrict the exploitation of these assets. Only in the EU (including Germany), which has relatively small indigenous fossil fuel reserves, has a reduction in the primary consumption of fossil fuels accompanied the expansion of NHRES. Therefore, NHRES technologies may be considered to have replaced fossil fuel technologies, with the consequence that the consumption of fossil fuels has decreased. This trend has a positive effect on security of supply, reducing the need for import of fossil fuels.

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