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Implications of energy and CO_2 emission changes in Japan and Germany after the Fukushima accident

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ABSTRACT

Following the March 2011 nuclear power plant accident in Fukushima, Japan, nuclear power production declined sharply in that country as well as Germany. Despite widespread media coverage of CO_2 emission increases in the first few years afterward, subsequent energy and emission changes and their implications are not well-studied. Here we analyze energy, electricity, and CO_2 emissions data for both countries through 2017. We also quantify the human health and CO_2 implications of two simple yet illuminating scenarios: What if both countries had reduced fossil fuel power output instead of nuclear? And what if the US and the rest of Europe eliminate their remaining nuclear power? We find that emissions increased after Fukushima until 2013 but decreased thereafter due to record-high renewable energy production and lower total energy use. However our "what if" scenarios demonstrate that these two countries could have prevented 28,000 air pollution-induced deaths and 2400 $MtCO_2$ emissions between 2011 and 2017. Germany can still prevent 16,000 deaths and 1100 $MtCO_2$ emissions by 2035 by reducing coal instead of eliminating nuclear as planned. If the US and the rest of Europe follow Germany's example they could lose the chance to prevent over 200,000 deaths and 14,000 $MtCO_2$ emissions by 2035.

1. Introduction

The Fukushima Daiichi accident (hereafter, simply "Fukushima" or "the accident") and its consequences have been scientifically assessed in several comprehensive UN studies (UNSCEAR, 2013; IAEA, 2015; UNSCEAR, 2016) and the numerous peer-reviewed papers discussed therein. These studies describe numerous direct and indirect radiological and socioeconomic impacts such as farmland and fishery contamination by radionuclides and long-term displacement of tens of thousands of nearby residents. However they reach the same general conclusion that widespread ecological or human health effects were not expected in the near or long term, with the notable exception of mental health impacts associated with the mass evacuations, loss of livelihoods, and fear of radiation fallout (and of nuclear power in general). Nevertheless, immediately following the accident the government of Japan greatly curtailed national nuclear power production, which was previously the third highest level in the world but is now the 14th highest of the 30 nuclear energy producing countries (BP, 2018; IEA, 2018a). A major reason for this reduction was implementation of enhanced safety protocols (Normile, 2018). As a result the future of nuclear power in Japan remains uncertain, though the government has adopted plans to restore the share of electricity from nuclear to over 20% by 2030, in part to enhance energy independence, which was significantly diminished after Fukushima (Government of Japan, 2018).

The accident also spurred Germany to adopt a goal of eliminating all domestic nuclear power production by 2022 (IEA, 2011; Arlt and Wolling, 2016). As of now these plans are still in place (IAEA, 2018a), though it remains to be seen whether they can realistically be achieved. Although this decision was consistent with longstanding and widespread anti-nuclear sentiment among the German public and had broad political and public support (Arlt and Wolling, 2016), it was nonetheless striking, given the lack of any serious nuclear accidents in Germany and the low likelihood of reactor-affecting natural hazards such as the earthquake and tsunami that caused Fukushima, as well as the decades-long record of nuclear power in preventing large amounts of greenhouse gas emissions and fatal particulate pollution that would have resulted from fossil fuel use (Kharecha and Hansen, 2013; Mielonen et al., 2015; Severnini, 2017).

In this study we analyze the nature and implications of post-Fukushima energy and CO_2 emission changes in both of these countries using empirical data covering 2000–2017 (Boden et al., 2017; BP, 2018; IEA, 2018a). Although emissions increases until 2013 garnered widespread international media coverage (e.g. Iwata, 2014; The Japan Times, 2014), we show that these increases were not persistent

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thereafter. This finding was somewhat surprising, given that nuclear energy provided a substantial fraction of non-fossil energy in both countries before the accident. We assess the reasons for this, while also quantifying the avoidable impacts of rapidly phasing down nuclear with regard to CO_2 emissions and human health. We accomplish the latter by analyzing a simple counterfactual scenario: What if Japan and Germany had reduced electricity production from coal by similar amounts as they reduced nuclear? The targeting of coal has strong basis given that it is the single largest source of cumulative historical emissions (Boden et al., 2017) and, like nuclear, it remains a key source of baseload electricity for much of the world, including these two countries (BP, 2018; IEA, 2018a). Lastly, we also examine the implications of a similar "what if" scenario for the world's top two nuclear energy users, the US and the rest of Europe (excluding Former Soviet Union).

2. Methods

2.1. TPE, electricity, and CO_2 emissions

For total primary energy use (TPE) and electricity generation we use the latest BP (formerly British Petroleum) and International Energy Agency (IEA) datasets (BP, 2018; IEA, 2018a). These datasets use two different energy accounting methods to convert electricity data to common energy units, which differ mainly in their assumptions regarding conversion efficiencies of individual power sources (for further details see Annex II of IPCC, 2014). These different methods can lead to discrepancies in TPE results for non-combustible energy sources in particular. The BP method generally leads to relatively high TPE values for several renewables including wind and solar. Nonetheless, the overall differences for both TPE and electricity data are fairly small (within a few %) for both the absolute data and the shares from each energy source (see Sections 3.1 and 3.2 and Supplementary Materials). As our primary study focus is the electricity sector, TPE data are shown only in the Supplementary Materials (Figs. S1 and S2). Because the annual data represent year-end values and the Fukushima accident occurred in March 2011, we take 2011 as the first year of the post-Fukushima period.

For annual TPE CO_2 emissions from fossil fuel burning we rely on archived data from US DOE-CDIAC (Boden et al., 2017), which end in 2014, and IEA (2018b), which end in 2016. Following previous methods of ours (Hansen et al., 2017, and refs therein) as well as CDIAC's, we extend these emissions data to 2017 by normalizing to BP energy use data for years 2015–2017 as follows, for a given fuel i and year t:

$$E(i, t) = E(i, t\text{-}1) \times BP(i, t)/BP(i, t\text{-}1), \quad (1)$$

where E(i, t) = CDIAC or IEA emissions and BP(i, t) = BP primary energy consumption data.

We separately calculate emissions from electricity generation based on emission factors from Table 2.2 of Ch. 2 of the IPCC (2006) guidelines – specifically 97.5 tCO_2/TJ for coal (average for the different types, i.e. anthracite [98.3], bituminous [94.6–96.1], and lignite [101]), 56.1 tCO_2/TJ for gas, and 73.3 tCO_2/TJ for oil. Because these factors relate to the intrinsic energy content of each fuel, we convert them to electricity-relevant values by dividing by an assumed thermal plant efficiency of 0.38 (following the BP [2018] method for converting electricity data into TPE data) then multiplying by 3600 J/Wh. This yields ~0.924 $MtCO_2$/TWh for coal, 0.531 $MtCO_2$/TWh for gas, and 0.694 $MtCO_2$/TWh for oil. Note that these values reflect combustion-stage emissions only (see Section 2.3). Carbon intensities (CI) are then calculated simply by dividing the corresponding emissions values by TPE, electricity, or GDP data (the latter are from World Bank, 2018). CI of TPE and electricity are shown in Section 3 and CI of GDP is shown in Fig. S3.

2.2. Avoidable impacts

In this study we define avoidable impacts as the CO_2 emissions and human health impacts that could have been avoided if instead of reducing nuclear electricity production after Fukushima, both countries had reduced their coal electricity production by equivalent amounts. For simplicity and transparency we adopt the general calculation approach of Kharecha and Hansen, 2013 (hereafter "KH2013"), with some modifications as described below. This method is justifiable in light of a subsequent study along similar lines (Mielonen et al., 2015) which used a sophisticated 3-D global aerosol-climate model and found remarkably similar results for mortality (within uncertainties), albeit with much higher mean annual values (which, as an aside, reinforces the assertion in KH2013 that the values therein are likely conservative). Note that we limit human health considerations in our study to premature mortality resulting from fatal air pollution due to fossil fuel use. Other significant health effects would of course also be expected – e.g. for fossil fuel power sources, serious illnesses tend to be about 10 times higher than mortality (see KH2013 and refs therein).

Following Eq. (4) of KH2013, we calculate annual avoidable impacts I(t) for years 2011–2017 as follows, for a given year t:

$$I(t) = [\ E(n, 2010) - E(n, t)\ ] \times [\ IF(c) - IF(n)\ ], \quad (2)$$

where I(t) = mortality or CO_2 emission impacts, n = nuclear, c = coal, E = electricity generation (from BP 2018), and IF = impact factor (mortality or emissions per TWh). The emission impact factor for coal is the one derived in Section 2.1. The mortality impact factor for nuclear is taken directly from Table 1 of KH2013, which as described therein, represents full life-cycle mortality from nuclear (including accident-related deaths among the public and plant workers).

For coal-related mortality impact factors, rather than using the value from KH2013 for IF(c) in Eq. (2), we derive modified values as follows. We start with the country-specific estimates for total outdoor air pollution deaths in 2010 from Table 2 of Lelieveld et al. (2015) and multiply each of them by the corresponding proportions from electricity generation in the same table. This yields total electricity sector-related outdoor air pollution deaths in 2010, which amount to ~4250 in Japan, 4420 in Germany, and 17,050 in the US. Using year 2010 values for fuel-specific pollutant emissions (SO_2 and NOx) from Table 7 of EIA's electricity data tables (EIA, 2018) we calculate that coal in the US accounts for 86.2% of these emissions. We then apply this proportion to the total electricity-related deaths listed above to derive the number of deaths caused by coal electricity production in each country. We believe this is a reasonable approach given broadly similar air pollution standards among developed countries and given the prime role of SO_2 and NOx emissions as chemical precursors to fatal particulates (Caiazzo et al., 2013; Dedoussi and Barrett, 2014; Thurston et al., 2016).

We then divide these coal-specific deaths by year 2010 coal electricity data for each country (averaged between the BP and IEA datasets). This yields mortality IF(c) values in Eq. (2) of 12 deaths/TWh for Japan, 14 deaths/TWh for Germany, and 8 deaths/TWh for the US. By comparison, KH2013 used a global value of ~29 deaths/TWh for coal, which as mentioned above yielded results broadly similar (though on average much lower) to a more sophisticated study (Mielonen et al., 2015) – thus, the mortality-related impacts we report here might likewise be quite conservative.

For Japan and Germany we use the above values for mortality impact factors, but for the US we note that there have been several studies besides Lelieveld et al. (2015) that quantify electricity-related air pollution mortality in the US. Specifically, Caiazzo et al. (2013), Fann et al. (2013), and Penn et al. (2017), which respectively estimate 52,000, 38,000, and 21,000 deaths from US electricity generation in 2005. Using the same method as above yields mortality IF(c) values for the US of 22, 16, and 9 deaths/TWh respectively based on these additional studies. Thus in our calculations for potential future avoidable impacts for both the US as well as the rest of Europe we use the average of the above four US values for mortality IF(c) in Eq. (2), i.e. 14 deaths/TWh. This has the added benefit of greater consistency with the mortality IF (c) values for Japan and Germany.

As with KH2013, note that $IF(c) \gg IF(n)$ in all cases, so I(t) in Eq. (2) is positive when nuclear electricity production has decreased relative to 2010, i.e. the pre-Fukushima level. Thus, positive values of I(t) in Eq. (2) represent avoidable deaths or emissions caused by post-Fukushima reduction of nuclear instead of coal. The numbers presented in Section 3.3 reflect the net sum of I(t) values over the relevant time periods.

Note that Eq. (2) uses nuclear electricity production in 2010 as the baseline. Results from alternative cases appear in the Supplementary Materials. We examine such alternatives only for Germany because its nuclear output exhibited a modestly declining trend for a few years before Fukushima, unlike in Japan (see Section 3).

We additionally examine avoidable impacts of proceeding to complete nuclear phaseout in Germany, the US, and the rest of Europe (excluding Former Soviet Union, where there are no indications that nuclear power will be reduced in the near future). Assuming an average reactor lifetime of 50 years and based on the start dates of commercial operation listed in Table 14 of IAEA (2018b), we assess that the current reactor fleets in these regions could last well into the 2030s. Thus we take the end year for our projection period to be 2035. For Germany we first assume a linear phaseout of all remaining nuclear output between 2018 and 2022, then fix nuclear output at zero until 2035. This yields values of E(n,t) for t from 2018 to 2035 in Eq. (2). Then, using 2017 as the new base year instead of 2010, the annual electricity difference term in Eq. (2) becomes E(n, 2017) - E(n, t), for t from 2018 to 2035. For the US and the rest of Europe we assume a simple linear phaseout of nuclear output over this same period (2018–2035). We take 2017 as the base year for these regions as well, so the Eq. (2) electricity difference term becomes E(n, 2017) - E(n, trend.2018–2035(t)), for t from 2018 to 2035. Results for these projection cases are reported in Section 3.3.

In addition to avoidable impacts resulting from our counterfactual scenarios, for Japan we also compute the potential mortality and CO_2 emission impacts caused by the actual post-Fukushima substitution of nuclear by fossil fuels that is discussed in Section 3.1. For each year t from 2011 to 2017 we now use the following equation instead of Eq. (2):

$$I(t) = [\ E(i, t) - E(i, 2010)\ ] \times IF(i), \tag{3}$$

where E(i, t) and IF(i) in this case denote electricity production and impact factor values for i = coal or gas only. (As we infer in Section 3.1, these two sources were the primary replacements for reduced nuclear in Japan. Note however that oil-based electricity production also increased after Fukushima, albeit temporarily, as shown in Section 3.1 – thus our results based on Eq. (3) are likely underestimates.) Emission factors for this case are the same as in Section 2.1. For mortality factors, we use the above value for coal in Japan (12 deaths/TWh) and, using a similar approach, we derive a factor for gas in Japan of 0.77 deaths/TWh. Here, positive values of I(t) represent directly caused deaths/emissions (as opposed to potentially avoidable ones), since fossil fuel use has increased from the base year 2010. In this case there is only one point at which I(t) is negative for either fuel – in 2011 coal electricity production decreased by 31 TWh. For reference, the net sums of additional coal and gas electricity production from 2011 to 2017 are 155 TWh and 633 TWh respectively (additional relative to their 2010 values).

2.3. Uncertainties and limitations

For similar reasons as discussed in KH2013, the main uncertainties in our analysis arise from our derived mortality impact factors. For example, this study likewise assumes static (i.e. time-independent) impact factors for Eqs. (2) and (3); in reality, these values are likely to change because they depend on the energy mix and emissions regulations of a given region. Specifically, mortality factors are likely to decrease with stricter controls on pollutant emissions from coal, which would generally lead to overestimates of avoidable mortality. On the other hand, new findings (Burnett et al., 2018) indicate that PM2.5-related mortality could be substantially higher than previously estimated, including by Lelieveld et al. (2015), whose results form the primary basis for our mortality factors (as discussed in Section 2.2). Given that these two sources of uncertainty essentially counteract each other, we take our mortality factors to be reasonable estimates for the time periods we analyze.

Nonetheless, in order to quantitatively include some uncertainty in these factors, based on the air pollution studies cited above to derive them (Caiazzo et al., 2013; Fann et al., 2013; Lelieveld et al., 2015; Penn et al., 2017), we conservatively prescribe the lower and upper bounds of uncertainty ranges (URs) in this study as 50% below and 30% above the central values, respectively. Thus, our mortality impact factors plus URs would be 12 (6–15.6) deaths/TWh and 0.77 (0.39–1.0) deaths/TWh for Japan's coal and gas, respectively, and 14 (7–18.2) deaths/TWh for coal in Germany, the US, and the rest of Europe. Results in Section 3.3 incorporate these URs.

Another source of uncertainty in our study relates to the precise causes of post-Fukushima energy system changes that we describe in Section 3 for Japan and Germany – i.e., conclusive attribution of subsequent changes to the accident itself (as opposed to other possible factors). Although such a causation analysis could be interesting in its own right, we do not include it because it would involve issues that are outside the scope of this study, such as utility decision making, energy economics, and distinction between residential and utility electricity production. Moreover, our fundamental goal is to describe the energy changes and assess their effects (implications) rather than their precise causes. For example, quantification of the health and environmental impacts that could have been avoided from post-Fukushima energy choices (Section 3.3) is rooted in the most important change relevant to our study: the sudden and large reduction of nuclear power output despite continued (and in some cases increased) fossil fuel power output. It is clear that this particular change is a direct consequence of post-accident energy choices, as shown in Sections 3.1 and Section 3.2 and references therein.

Lastly, our mortality impact factor for nuclear is based on life-cycle analysis that includes accident-related deaths among the public and plant workers and is taken from KH2013. For fossil fuels though, our impact factors are based only on the combustion stage, thus they do not represent all potential damages. However for fossil fuels the vast majority of health-related impacts as well as emissions result from the combustion stage (Markandya and Wilkinson, 2007; IPCC, 2014), therefore this is not a significant limitation.

3. Results and discussion

3.1. Japan

Electricity generation in Japan shows a modest long-term decline (< 10% between 2000 and 2017; Fig. 1a), with a 2017 value that is 4% of the world total. This overall decline continued after Fukushima, although the proportion of electricity from fossil fuels increased from 64% in 2010 to 78% in 2017 (Fig. 1b). This increase appears to be a direct result of the share of nuclear plummeting after the accident from 25% in 2010 to zero in 2014. However it has marginally increased since then, reaching 3% at the end of 2017 (Fig. 1b). Furthermore, although 13 of Japan's reactors have been permanently shut down since the accident, 42 remain on standby (representing 85% of pre-Fukushima nuclear *capacity*) and two reactors are under construction with 9 more planned (IAEA, 2018b).

A detailed breakdown by individual electricity sources (Fig. 1a), along with the fact that Japan has neither imported nor exported any

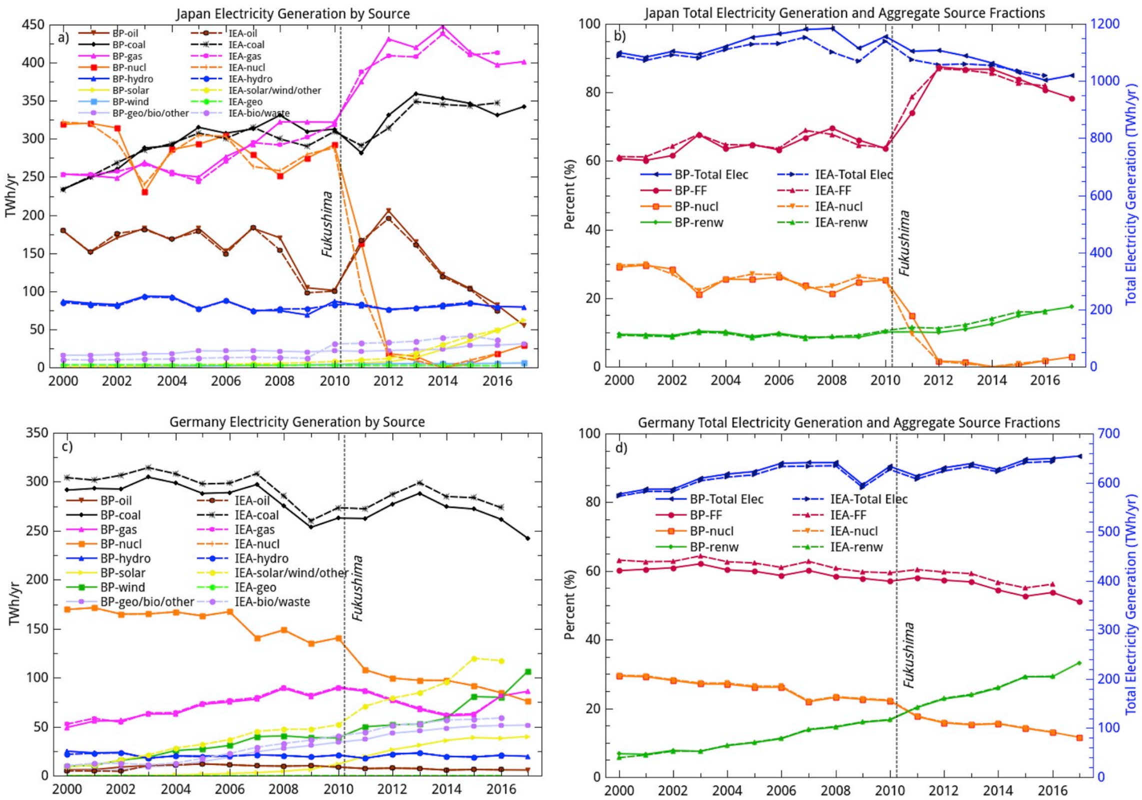

Fig. 1. Electricity generation by source (left) and total electricity generation and aggregate source fractions (right) for Japan (top) and Germany (bottom), 2000–2017. Data are from IEA (2018a) and BP (2018). Dashed vertical lines labeled "Fukushima" represent the timing of the accident. All annual values are taken to be end-year values, hence we consider 2011 the first year after the accident. FF = fossil fuels, geo/bio = geothermal + bioenergy, renw = all renewables (hydro + non-hydro). See Fig. S2 for cumulative post-Fukushima shares of electricity.

electricity for decades (IEA, 2018a), shows that gas and coal have evidently been the primary replacements for lost nuclear, with their combined share of total electricity rising from 55% in 2010 to 73% in 2017. Electricity production from oil also increased for the first two years after Fukushima but then declined thereafter. Renewable share increased from 11% in 2010 to 19% in 2017 (Fig. 1b). This increase was driven mainly by expanding solar energy, the share of which grew from near-zero in 2010 to 6% in 2017 (Fig. 1a).

As shown in Fig. 2a, total CO_2 emissions from TPE in Japan amounted to 1144 $MtCO_2$/yr in 2017 (5th highest in the world) and have been more or less steady since 2000, with the dominant sources in 2017 being oil and coal (~40% each) followed by gas (20%). After Fukushima, emissions increased modestly until 2013 then slightly decreased between 2014 and 2017. This decrease was largely driven by a decline in oil emissions between 2013 and 2017 from the electricity sector (see next paragraph). Coal and gas emissions both increased very slightly in 2017, returning total emissions to the pre-Fukushima (2010) level. Carbon intensity of TPE exhibits sustained increases after Fukushima and remains elevated relative to 2010 (inset in Fig. 2a). The discrepancies between the IEA and BP inset curves arise due to the energy accounting differences described in Section 2.1.

Unlike TPE emissions, total electricity-sector CO_2 emissions in Japan (which we compute ourselves; see Section 2.1) show a long-term increase since 2000, reaching 570 $MtCO_2$/yr in 2017 (Fig. 3a). After Fukushima they follow a broadly similar pattern as TPE emissions but with greater interannual changes and different dominant sources (i.e. coal and gas as opposed to coal and oil in TPE). These emissions remain higher than the pre-Fukushima level by ~10% (Fig. 3a), and account

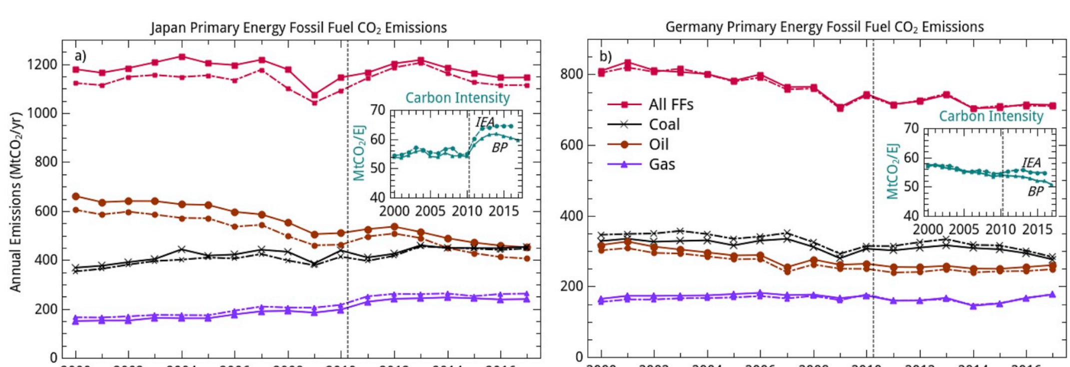

Fig. 2. Annual primary energy fossil fuel CO_2 emissions for a) Japan and b) Germany, 2000–2017. Emission data are from US CDIAC archives (solid lines; Boden et al., 2017) and IEA (dashed lines; IEA, 2018b) and have been extended to 2017. All FFs = all fossil fuels combined. Inset graphs show carbon intensity (CI) of TPE, computed using CDIAC emission data and IEA and BP energy data.

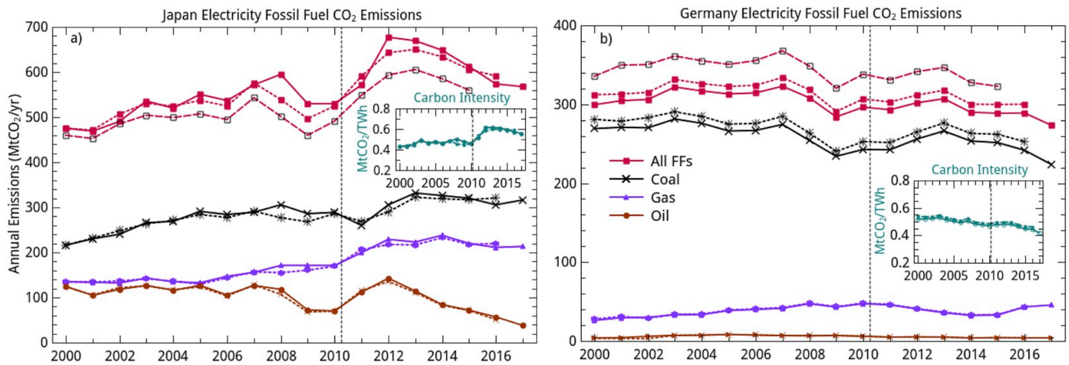

Fig. 3. Annual electricity sector fossil CO_2 emissions for a) Japan and b) Germany, 2000–2017. Solid and dashed lines are based on BP (2018) and IEA (2018a) electricity data, respectively. All values are original calculations except for the open square curves, which are directly from IEA (2018b) and end in 2015. All FFs = all fossil fuels combined. Our results for total emissions agree well with the IEA data overall (within ~10% for each year). Inset graphs show CI of electricity; unlike in Fig. 2 the IEA/BP inset curves are not labeled separately here because they are almost identical (because the underlying electricity data are almost identical).

for a gradually increasing share of TPE emissions since 2000 (Fig. S4), a trend which has accelerated after Fukushima. Carbon intensity of electricity increased significantly from 2011 to 2013 then decreased thereafter, though it remains higher than in 2010 (inset in Fig. 3a). However it could return to lower levels if nuclear power production resumes per the government's plans (Government of Japan, 2018). CI of GDP (Fig. S3) has been steadily declining since 2000 (except for a post-Fukushima increase from 2011 to 2013), reflecting decoupling of Japan's economic growth and CO_2 emissions.

If the TPE emissions trend from 2013 to 2017 is extrapolated to 2030 (Fig. 4a), we find that Japan would achieve its stated Nationally Determined Contribution (NDC) under the 2015 Paris Agreement, which aims for 26% lower emissions in 2030 versus 2013 (UNFCCC, 2018). However this NDC is weaker than previous pledges due to post-Fukushima energy changes (Kuramochi, 2015). Furthermore if emissions are extrapolated from 2011 instead of 2013, Japan will overshoot its NDC by 144 $MtCO_2$/yr (+16%; Fig. 4a). Compensation of this overshoot should be feasible though, e.g. via a combination of continued total electricity use reduction, reduced coal and gas emissions, increased nuclear and renewable energy production, and other emissions-cutting measures. However Japan's climate change and air pollution mitigation goals will likely be seriously undermined by the dozens of recently built or planned coal-fired power plants (Kuramochi, 2015; Normile, 2018). Moreover, by the UN's own assessments (UNFCCC, 2016; UNEP, 2017) and other scientific analyses (Rogelj et al., 2016), the aggregate effect of national NDCs would lead to global temperatures well above 2 °C – a target which itself is highly dubious in terms of "safety" (Knutti et al., 2015; Hansen et al., 2017).

3.2. Germany

Total electricity generation in Germany shows a clear long-term increase in both the IEA and BP datasets (~13% between 2000 and 2017; Fig. 1c and d), with a 2017 value that is 2.6% of the world total. This increasing trend largely continued after Fukushima. The proportion of electricity from fossil fuels decreased from 57% in 2010 to 51% in 2017 (Fig. 1d), while the share of nuclear essentially halved. Unlike with Japan, the latter was a result of rapid reduction of overall reactor number and capacity, both of which fell by over 50% between 2010 and 2017 so that there now only 7 operational reactors left nationwide (IAEA, 2018b).

As discussed in Section 2.3, although a detailed attribution analysis of the causes of post-Fukushima electricity changes is outside the scope of this study, at face value these changes reveal some interesting dynamics. Based on aggregated source data alone (Fig. 1d) it might appear that Germany's post-Fukushima reduction of nuclear was replaced by increased renewables. A closer examination of the individual sources (Fig. 1c) suggests that, at least in the first year following the accident (2011), this indeed seems to have happened, for three key reasons: 1) non-hydro renewables (wind, solar, and bioenergy) increased in 2011 while all other significant sources (coal, gas, oil, nuclear, and hydro) decreased; 2) total electricity production decreased by only half the sum of the individual decreases; and 3) Germany was a net exporter of electricity in 2011, as it has been every year since 2003 (and its exports have continually increased since Fukushima; see Fig. S5). If this qualitative attribution analysis is correct for 2011, this apparent substitution is somewhat surprising, given the different nature of these energy

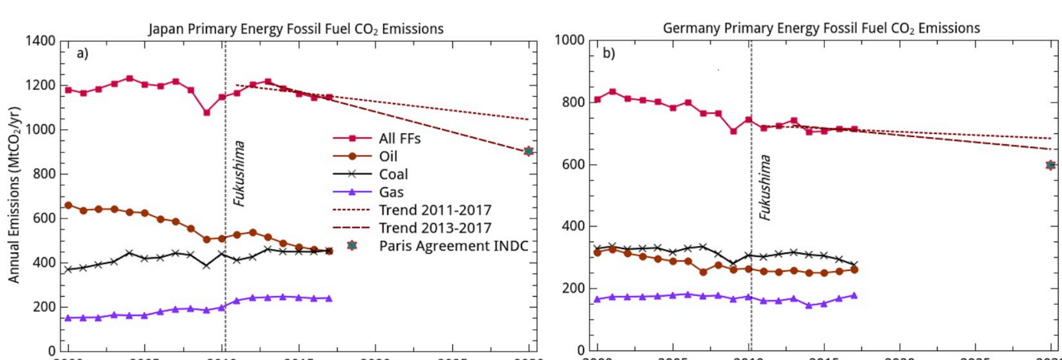

Fig. 4. TPE CO_2 emissions by source in a) Japan and b) Germany compared to each country's Paris Agreement Intended Nationally Determined Contributions (NDCs). For simplicity only the CDIAC data from Fig. 2 are included for the historical period (solid lines). Two sets of extrapolations are shown (dashed lines): one based on the full post-Fukushima (2011–2017) emission trends and the other using 2013–2017 emission trends only. The latter represents a stronger decreasing trend because post-Fukushima emissions peaked in 2013 in both countries.

sources – i.e. nuclear, hydro, and fossil fuels provide continuous (baseload) power whereas solar and wind provide variable power.

However as shown in Fig. 1c, in the subsequent two years (2012 and 2013) coal and hydro increased in addition to non-hydro renewables. Then from 2014 to 2017, electricity production from coal resumed its pre-Fukushima decline, dropping from 44% of total electricity in 2010 to 37% in 2017. Total renewables now account for a record one-third of total national electricity production (Fig. 1d), almost entirely from non-hydro sources, i.e. wind (16% of total), solar (6%), and biomass/geothermal (8%). For the past three consecutive years though (2015–2017), electricity from gas has risen substantially – it is now over 40% higher than in 2014 (Fig. 1c).

Fig. 2b shows that CO_2 emissions from TPE in Germany were 715 $MtCO_2$/yr in 2017 (6th highest in the world) and they exhibit a modest long-term decline since 2000, with the individual sources in 2017 amounting to 39% (coal), 36% (oil), and 25% (gas). Emissions decreased in the first year after Fukushima (2011) then increased to 2013 and decreased overall thereafter, with the level in 2017 being slightly lower than in 2010. However emissions from gas use have risen 22% over three consecutive years (2015–2017), concomitant with the rise in electricity from gas described above. If the latter trend continues it could substantially hinder Germany's climate change mitigation efforts.

Total electricity-sector CO_2 emissions in Germany reached 273 $MtCO_2$/yr in 2017, slightly lower than the pre-Fukushima level (Fig. 3b). Emissions from gas remain far lower than those from coal, however their relative increase is even more significant than with TPE (+41% between 2014 and 2017). Unlike with Japan, carbon intensities of TPE and electricity changed relatively little after Fukushima (insets in Figs. 2b and 3b). Electricity-sector emissions have accounted for a near-steady share (~40%) of overall emissions from 2000 onwards (Fig. S4).

If Germany's TPE emissions trend from 2013 to 2017 is extrapolated to 2030 (Fig. 4b), it would overshoot its NDC by 52 $MtCO_2$/yr (+9%). The NDC is based on the EU-wide goal, which aims for 40% lower emissions in 2030 versus 1990 (UNFCCC, 2018). If emissions are extrapolated from 2011 onward instead, the overshoot increases to 87 $MtCO_2$/yr (+15%). As with Japan, compensation of either overshoot should readily be feasible (adequacy of the NDCs notwithstanding), in this case if Germany even partially refrains from phasing out all of its remaining nuclear and instead curtails coal, which would also greatly benefit human health (see next section).

3.3. Avoidable impacts: missed opportunities

Finally, we examine avoidable impacts arising from electricity production changes after Fukushima by quantifying the mortality and CO_2 emissions that could have been prevented if these countries had reduced coal instead of nuclear. For Japan we additionally quantify the consequences of actually having replaced nuclear with fossil fuels (coal and gas).

We find that Japan could have prevented up to 21,000 (UR: 10,500–27,300) premature air pollution-related deaths and 1700 $MtCO_2$ cumulative emissions from coal burning between 2011 and 2017 (Fig. 5). Furthermore Japan's post-Fukushima energy choices might have caused another 2300 (UR: 1150–2990) deaths and 480 $MtCO_2$ cumulative emissions due to the cumulative addition of 789 TWh from coal and gas since the accident. These avoidable indirect consequences of Fukushima have compounded the devastating loss of life from the earthquake and tsunami that caused the accident in the first place.

Likewise, Germany could have prevented up to 4600 (UR: 2300–5980) deaths and 300 $MtCO_2$ cumulative emissions between 2011 and 2017. And if the country proceeds to total nuclear phaseout by 2022, it could lose the chance to prevent an additional 16,000 (UR: 8000–21,000) deaths and 1100 $MtCO_2$ cumulative emissions compared to a case in which its nuclear output remained steady at the 2017 value until 2035 (Fig. 5; see Fig. S6 for alternative cases). Careful (re)consideration of this near-term trajectory would thus seem warranted, especially in light of Germany's mitigation goals and the forecasted NDC overshoot discussed in the previous section and shown in Fig. 4.

This analysis of avoidable impacts has important implications for other major nuclear power producers. For example, there are credible assessments suggesting that nuclear could decline significantly in the US as well as the rest of Europe in the next few decades (Kunsch and Friesewinkel, 2014; Morgan et al., 2018). If we suppose that these regions adopt Germany's goal of total nuclear phaseout (whether intentionally or due to unfavorable market conditions or other factors) in a linear fashion between 2018 and 2035, we find that they could each lose the chance to prevent over 100,000 (UR: 50,000–130,000) air pollution-induced deaths and 6800–7400 $MtCO_2$ cumulative emissions from coal burning (Fig. 5). These avoidable trajectories would surely complicate these regions' stated climate change mitigation goals (UNFCCC, 2018), in addition to worsening outdoor air pollution-related mortality and serious illnesses, which are already substantial in both regions and projected to increase further if current energy policies continue (Lelieveld et al., 2015).

4. Conclusions and policy implications

Although CO_2 emissions increased in Japan and Germany in the first three years after Fukushima, both countries have managed to reduce their emissions thereafter despite large reductions of nuclear energy, which until recently was a major source of non-fossil baseload power in both countries. However both countries have experienced small but persistent emissions increases in the last year or two. Thus it remains to be seen what paths their near-future emissions will take, especially given record-high levels of electricity from variable renewables, which often rely on fossil fuels for backup (given the current lack of utility-scale energy storage).

Moreover, by sharply reducing nuclear instead of coal and gas after

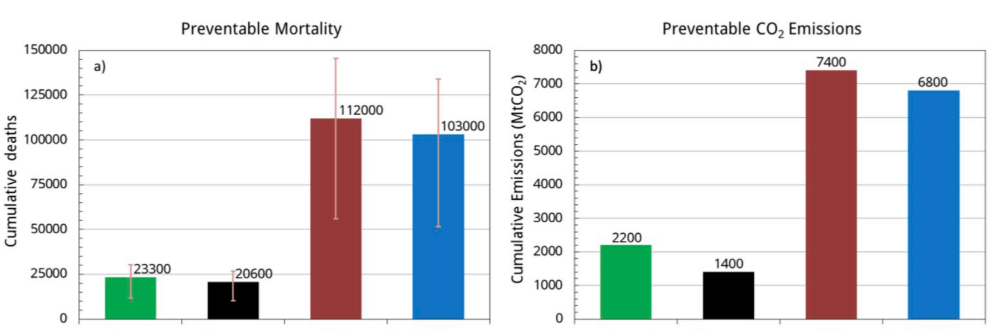

Fig. 5. Avoidable impacts caused by reducing nuclear instead of fossil fuels in four major energy using regions. Values are cumulative preventable a) mortality from outdoor air pollution caused by fossil fuel use and b) fossil fuel CO_2 emissions over various time periods. Error bars denote uncertainty ranges (see Section 2.3). For Japan these results represent the sum of impacts from the real-world substitution of nuclear by fossil fuels after Fukushima (mostly gas and coal) plus impacts from our hypothetical "what if" scenario. Values for Germany reflect sums over two time periods: post-Fukushima (2011–2017) and 2018–2035. Values for the US and the rest of Europe (excluding Former Soviet Union) reflect sums over 2018–2035 and are particularly high because they are the world's largest nuclear power producers.

Fukushima, both countries lost the chance to prevent very large amounts of air pollution-induced deaths and CO_2 emissions, which will further complicate their national climate change and air pollution mitigation efforts. However there are some encouraging developments: in Japan nuclear electricity production is increasing, and there are plans to increase its share of total electricity to pre-Fukushima levels (~ 20%) and to increase renewables to similar levels while reducing fossil fuels. Germany also has ambitious plans to decarbonize its electricity sector, and as our analysis shows, reducing coal instead of (or at least prior to) phasing out remaining nuclear would greatly enhance such efforts.

Our analysis has similar implications for other major nuclear and fossil energy users such as the US and the rest of Europe: it would be far more beneficial for the health of their populations and their mitigation efforts if they curtailed electricity production from coal and gas before or instead of phasing out nuclear.

Author contributions

P.K. conceived the study and designed the analysis; P.K. and M.S. performed the calculations and created the figures; P.K. wrote the paper with feedback from M.S.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2019.05.057.

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