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Effects of nuclear power plant shutdowns on electricity consumption and greenhouse gas emissions after the Tohoku Earthquake

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ABSTRACT

This study analyzes how the substitution of fossil fuels for nuclear power due to the shutdown of nuclear power plants after the Tohoku Earthquake affects electricity consumption and greenhouse gas emissions in Japan. Results indicate that Japan generated 4.3 million metric tons (or 0.3%, with a 95% confidence interval) of additional CO_2 emissions in 2011 following the earthquake. The increase in CO_2 emissions stemmed from the combined effects of decreased electricity consumption due to energy conservation efforts and the substitution of fossil fuels for nuclear power following the Tohoku Earthquake. Results also show considerable spatial variation in the impacts of the earthquake on net CO_2 emissions. A majority of the prefectures (40 of 47 prefectures, or 85%) were predicted to experience higher CO_2 emissions after the Tohoku Earthquake while the remaining (7 prefectures) were predicted to experience lower CO_2 emissions. Our findings suggest that Japan and countries under similar risks may want to reformulate energy policy by emphasizing utilization of diverse power and energy sources, including more renewable energy production and electricity conservation. The policy reform should also consider spatial variation in the combined effects of reduced reliance on nuclear power and increased CO_2 conversion factors.

1. Introduction

Japan experienced a devastating earthquake and tsunami off the Pacific coast of the Tohoku region in March 2011 (hereafter referred to as "the Tohoku Earthquake"). The Tohoku Earthquake caused widespread casualties and damage throughout the Pacific coastal region of Japan. Approximately 16,000 people lost their lives and 220,000 houses were destroyed. Parallel devastation resulted from the tsunami-induced Fukushima nuclear reactor meltdown, affecting the livelihood of the population over an extensive area. Following the Fukushima nuclear reactor meltdown, the Japanese government shut down all existing nuclear power plants, at least in the short term, because of safety concerns (Johnston, 2011). With the shutdown came a reduced power supply for almost the entire population. For example, Kansai, a region in the west that was not directly affected by the Tohoku Earthquake, suffered power shortages during the winter of 2011 (Tsukimori, 2011). These power shortages are being addressed through energy conservation efforts and increased fossil fuel use (Endo, 2011; Park, 2014).

We seek to understand how the substitution of fossil fuels for nuclear power due to the shutdown of nuclear plants after the Tohoku Earthquake affects electricity consumption and GHG emissions across regions in Japan. Specifically, we test the hypotheses that (i) the combined effects of reduced electricity consumption and increased use of fossil fuels resulting from the Tohoku Earthquake have led to a net increase in GHG emissions in Japan, and (ii) the combined effects vary spatially across the country.

Hypothesis (i) is based on the premise that reduced electricity consumption reduces GHG emissions while switching from nuclear power to fossil fuels increases GHG emissions—electricity generation from fossil fuels produces GHG emissions, whereas nuclear power emits no or minor amounts of GHG emissions (Jenkins and Caine, 2012). After the earthquake, electricity consumption declined because of the combination of extensive damages to power stations along the Pacific coast and electricity savings led by a national campaign known as "Setsuden" (saving electricity) (Myllyvirta and Guay, 2014). These two effects reduced Japan's annual energy consumption by 4.2% in 2012 compared with 2010, during which time the percentage of power from fossil fuels increased by 21% (U.S. EIA, 2013; ANRE, 2014). The greater percentage increase in the share of fossil fuel relative to the percentage decrease in energy consumption suggests that fossil fuel substitution may have increased GHG emissions more than the decline in electricity

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consumption reduced GHG emissions. Formally, our test for hypothesis (1) is whether the net change in CO_2 emissions after the earthquake is positive when the effects of lower electricity consumption and the substitution of fossil fuels for nuclear power are combined.

Hypothesis (ii) is based on three considerations. First, the reliance on nuclear power before the Tohoku Earthquake varied considerably across regions (ranging from 0% to 56% of a prefecture's power supply during 1990–2008); thus, the impacts of the nuclear plant shutdown on the substitution of fossil fuels for nuclear power, and the consequent effects on GHG emissions, are likely to differ by region. Second, lower electricity consumption varied across regions (e.g., the reduction in power demand in the service areas of Tokyo Electric Power Company and Tohoku Power Company was almost 20% in the summer of 2011 relative to 2010, compared with a 12% nationwide reduction), hence GHG emissions related to reduced electricity consumption are expected to vary across regions (Kimura and Nishio, 2013). Third, the spatial spillover effects of reduced electricity consumption and fossil fuel substitution are expected to vary spatially, resulting in different impacts on GHG emissions by region. Consequently, the combined effects of reduced electricity consumption and increased use of fossil fuels on GHG emissions are expected to vary spatially. Formally, our test for hypothesis (2) is whether the net change in CO_2 emissions after the earthquake varies spatially as a result of lower electricity consumption and the substitution of fossil fuels for nuclear power.

Nuclear power averaged 30% of Japan's total energy consumption from 1987 to 2011, whereas power generation from nuclear plants was zero in 2014 (U.S. EIA, 2015). Consequently, nuclear power was replaced by fossil fuels, the share of power from fossil fuel rising from 62% to 88% during the four years after the Tohoku Earthquake. With increased dependence on mostly imported fossil fuel, household energy expenses increased an average of 13.7% over the same period (World Nuclear Association, 2015). As a result, electricity consumption per capita decreased from its historical high of 8474.38 kWh in 2007 to 7752.49 kWh in 2012 (The World Bank, 2015).

The significant reduction in energy consumption and dramatic increase in fossil fuel use are expected to affect the country's total greenhouse gas (GHG) emissions in the short run. Accordingly, the Japanese government is seeking to adjust its GHG emissions target. Japan announced a revised 2020 GHG emissions reduction target of 3.8% from the 2005 level at the 19th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCC) (Sankei News, 2012; Kuramochi, 2014).

While the Japanese government has been quickly responding to the Tohoku Earthquake by adjusting the emissions mitigation target, it is still not clear how the shutdown of nuclear plants affects electricity consumption and GHG emissions. Understanding these effects is important in overcoming the country's challenges of securing its energy supply and revising its climate change mitigation policies, because the increased dependence on fossil fuel is expected to continue at least in the short term given public uneasiness with nuclear power (Bukoski, 2015). A recent study (Squassoni, 2011) finds that the Fukushima crisis heightened the general public's concern about radiation in Japan, even though the effects have been mostly local. In response to this concern, the country is making efforts to reduce the role of nuclear power, yet minimizing the use of fossil fuel as its energy supply recovers. For example, the Innovative Strategy for Energy and the Environment in 2012 calls for power generation from renewables to triple compared to 2010 levels, reaching about 30% of total generation by 2030 (IEA, 2012). Despite this ambitious plan, increased dependence on fossil fuel is inevitable in the near future because the renewable energy market in Japan is still in its infancy (Portugal-Pereira et al., 2013). Japan's share of renewable energy in total power generation, while increasing gradually, has been relatively low, e.g. 4.7% in 2013 (JFS, 2015).

Since the Tohoku Earthquake, large-scale power outages have occurred in two of ten service areas (i.e. Tokyo Electric Power Company and Tohoku Power Company) (see Fig. 1 for the map of the service areas and the Fukushima nuclear reactor).[1] The potential power shortages were managed by planning blackouts on an area-by-area basis (Bruch et al., 2011; Kimura and Nishio, 2013). The Japanese government's electricity-saving strategy included mandatory rationing by large industry, information campaigns, and technical energy saving assistance (IEA, 2011). For example, the government required the industry sector to cut electricity consumption by 15% during July through September of 2011 compared with the same period in 2010. Furthermore, a governmental task force was formed to conduct a multidimensional energy-saving information campaign. As a major effort, electricity-saving strategies were developed for the medium and small business sectors (IEA, 2011).

Although uncertainty remains about the re-opening of Japanese nuclear power plants and the increased reliance on fossil fuel in the long term, greater use of fossil fuels in the near future seems inevitable. While the government's plan has ignited public debate about whether restarting nuclear plant operation is prudent, two of eleven nuclear reactors were restarted briefly during July 2012 through September 2013 in the Kansai region because of vulnerable energy supplies. As of this writing (December 2015), these two reactors returned to commercial operation in September and November 2015, leaving 46 of 48 nuclear reactors shut down, although the government has been trying to restart nuclear plants in the Kansai, Shikoku, and Kyushu regions of western Japan (Japan Nuclear Technology Institute, 2015). Since the Tohoku Earthquake, supplies have been vulnerable and electricity prices have increased significantly because more than 50% of the country's energy came from nuclear plants prior to the shutdown (Fackler, 2012).

2. Literature review

The following key issues associated with our hypotheses have been addressed in the literature: (1) the economic and ecosystem impacts of catastrophic events and (2) the spatial structure of economic and ecosystem impacts of catastrophic events. The studies dealing with issue (1) have focused on the relationship between catastrophic events and economic response including energy consumption and the impacts of catastrophic events on ecosystems such as GHG emissions. Most assessments of the economic impacts of catastrophic events have focused on the most easily measured direct losses such as the financial cost of visible physical damage (e.g., building damages and bridge collapse) (NAS, 1999; Whitworth et al., 2006; Bilgehan and Kilic, 2008; Msilimba, 2010; Petrucci, 2012). This kind of analysis aims to understand the short-term needs of the affected population in the aftermath of a catastrophic event (Benson and Clay, 2003). A shortcoming of these studies is that tracing the effects of disaster-induced losses is difficult (Wu et al., 2012). Successful empirical modeling of the economic impacts of a catastrophic event should improve the shortcoming of studies focusing on direct losses. A comparison of economic variables (e.g., per capital income) with and without the event using a simulation-based empirical model can trace the disaster-induced economic effects, helping policy makers evaluate the consequences of catastrophic events (Ellson et al., 1984).

Large-scale catastrophic events such as earthquakes, tsunamis, volcanic eruptions, fires, and climatic phenomena can have prolonged effects on ecosystems (Atwater, 1987; Atwater and Moore, 1992; Nelson and Manley, 1992; Foster et al., 1998; Franklin and MacMahon, 2000; Turner, 2005; Turner, 2010). Many studies that deal with ecological impacts of catastrophic events focus on estimating disturbances caused by natural disasters on various ecosystems (NAS, 1999; Brodie et al., 2008; Kuppusamy, 2008; Goldman, 2011; Freund, 2015). For example, research on the ecological impacts of the Tohoku Earthquake Tsunami on aquatic animals in rice paddies was conducted based on field data collected at six sites along the coast of Miyagi Prefecture (Mukai et al.,

[1] Japan has ten privately owned electric power companies that are in charge of regional power supply services (http://www.fepc.or.jp/english/energy_electricity/company_structure/).