

EVALUATING THE EFFECT OF INTERMITTENT RENEWABLES ON THE
WHOLESALE ELECTRICITY MARKET IN GERMANY

by

Andrew Adelfio

Dr. Lincoln Pratson, Adviser

April 2014

Master's Project submitted in partial fulfillment of the
Requirements for the Master of Environmental Management degree in
The Nicholas School of the Environment of
Duke University

2014

Abstract

For years, Germany has been a pioneer in the aggressive build out of intermittent renewables (solar and wind). The Energy Concept launched in 2010, in conjunction with previously established federal energy policies, has further enhanced Germany's ability to reach lofty renewable generation targets via ratepayer surcharges that support feed-in tariffs. However, as the penetration of renewables has increased, wholesale electricity prices have demonstrated a steady decline. Through statistical and market-based analysis, this project 1) quantifies the price decrease that is caused by build out of renewables, 2) examines the market mechanics that result in a price decrease, and 3) evaluates the effect of the price decrease on relevant electricity market participants.

Regression analysis indicates that average wholesale electricity prices will experience a decrease of 6.5 €/MWh – 8.5 €/MWh by 2020, solely due to the build out of renewable energy to comply with Energy Concept targets. Based on current electricity demand, this price reduction will result in an annual revenue loss of €2.96 billion – €3.88 billion. Importantly, this revenue loss will not be distributed equally amongst wholesale generators. Generators with higher marginal costs will be affected disproportionately because the frequency with which they can be dispatched profitably will decrease more than for cheaper generators. Specifically, this will hurt natural gas plants, many of which will be phased out due to unfavorable economics. This loss of natural gas plants will 1) present challenges to the grid's ability to maintain stability while introducing more intermittent renewables and 2) force Germany to remain reliant on carbon-rich coal for electricity. The findings of this study are then applied to other locations that are also pursuing aggressive renewable energy targets.

Contents

Introduction..... 1
Methods..... 4
Results..... 6
Discussion..... 13
Literary Citations 20

Figures

Figure 1. Cumulative Supply Curve. 7
Figure 2. Wholesale Electricity Price vs. Hourly Demand..... 8
Figure 3. Wholesale Electricity Price vs. Hourly Demand for Every Hour in 2013. 9
Figure 4. Percentage of Generation Provided by Renewables vs. Wholesale Electricity Price..... 10
Figure 5. 2013 Wholesale Electricity Prices – Histogram and Normal PDF..... 12
Figure 6. Current Price PDF vs. 2020 Price PDF with Generator-Specific Marginal Costs. 12

Tables

Table 1. Simple Regression Summary (Renewables vs. Price). 10
Table 2. Multiple Regression Summary (Renewables vs. Price). 11
Table 3. Comparison of Dispatch Probability Following 2020 Wholesale Price Decrease. 13

Introduction

For years, Germany has been a worldwide pioneer in the build out of renewable energy. On an annual basis, approximately one quarter of Germany's electricity is produced by renewable energy sources (Federal Statistical Office of Germany, 2014; Germany.info, 2012). Germany's build out of renewable energy has been primarily tied to the German Renewable Energy Act, which was implemented in 2000, and its 1991 predecessor, the Electricity Feed-In Act (Meza, 2013; Held et al., 2007). National policy has continued to incentivize the development of renewable power sources, particularly following the Fukushima Daiichi nuclear plant incident in Japan, after which the Germans government has decided to phase out its nuclear reactors by 2022 (Post, 2011).

Germany's newest iteration of national energy policy was launched in 2010. The "Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply" (hereafter referred to as the "Energy Concept") serves as a long-term strategy with periodic goals extending through 2050 (BMU, 2010; GTAI, 2014). In addition to specific carve-out goals, the Energy Concept set a general target that 35% of Germany's electricity must be supplied by renewable energy sources by 2020. This target subsequently increases to 80% by 2050. The Energy Concept, which uses market-based incentives such as feed in tariffs and tax credits, is financed through a combination of government spending and rate-payer surcharges (Germany.info, 2012).

In order to reach the target of renewable energy sources supplying 35% of electricity by 2020, the generation of renewables must increase by approximately 10% within the next 6 years. Conventional hydroelectric power, which currently supplies 3.2% of electricity, is relatively saturated in Germany – build out of turbines is now limited by the availability of suitable sites and the associated disruptions to local ecosystems (DENA, 2012). Energy policy such as the

Energy Concept has specifically pegged wind and solar (currently comprising 8.4% and 4.7% of total electricity, respectively) as the sources of growth toward renewable energy targets (Federal Statistical Office of Germany, 2014). The Energy Concept provides support for the build out of wind and solar by requiring grid operators to give priority to renewable energy. Also, ratepayers pay surcharges that are passed onto renewable energy generators via a feed-in tariff, which is a fee above the retail price of electricity. While the feed-in tariff varies depending on the type of renewable energy technology, the average surcharge to ratepayers is 0.036 €/kWh, which contributes to the extremely high retail electricity prices seen in Germany (Eurostat, 2013 and Germany.info, 2012).

Unlike other sources of conventional and renewable energy, solar and wind provide intermittent power generation. Their generation capabilities are closely tied to environmental factors (e.g., wind speeds, solar insolation), so the contribution of both solar and wind generators to meeting demand is relatively hard to predict. This intermittent aspect of solar and wind, combined with the aggressive build out prescribed by the Energy Concept, has led to some concern about Germany's ability to meet its renewable portfolio goals without compromising grid stability.

Studies have indicated that recent events in the German electricity markets have been closely tied to this build out of intermittent renewables. One significant effect has been a steady decline in wholesale electricity prices. Average electricity prices have dropped from 80 €/MWh in 2008 to under 40 €/MWh in 2013 (Economist, 2013). These declining prices have coincided with the recent build out in renewables. Because the build out of renewables has been aggressive, the growth of total electricity production capacity within Germany has outpaced any increases in demand (Economist, 2013). Because the ratio of supply to demand has increased, economic

forces have driven wholesale electricity prices downward. Although wholesale prices have decreased by more than 50% in the last 5 years, retail electricity prices have exhibited a contrasting trend.

Despite the steady reduction in wholesale electricity prices, savings have not been passed along to end consumers. Electricity consumers in Germany pay some of the highest electricity rates in the world. Second in Europe only to Denmark, retail electricity rates in Germany were 0.292 €/kWh, which is about three times higher than the 0.117 \$/kWh rate in the United States, after accounting for currency exchange (Eurostat, 2013; EIA, 2014a). Contributing to the discrepancy between wholesale prices and retail prices is the aforementioned ratepayer surcharge of about 0.036 €/kWh, which is paid by retail customers but is not received by wholesale generators (Germany.info, 2012). Instead, these surcharges are used to subsidize the feed-in tariffs that provide 20 years of guaranteed prices to renewable energy generators (Germany.info, 2012).

Other recent events indicative of the impact of renewables have been negative wholesale electricity prices. Negative intraday prices first occurred in 2007 and negative day-ahead prices were introduced in 2008 (EPEX, 2014a). Because grid operators must match electricity supply and demand in real time, negative prices are used to signal excess supply relative to demand (EPEX, 2014a). Therefore, individual generators are able to compare their internal economic tradeoffs that result from either paying money to generate electricity or incurring costs related to shutting down and coming back online. In 2013, electricity markets reached the negative price cap of 100 €/MWh set by the European Power Exchange (Economist, 2013; EPEX, 2014a). The increase in magnitude and frequency of negative electricity prices, coupled with the decrease in

average wholesale electricity prices, has led to concerns over the ability of wholesale electricity generators to operate profitably and continue to provide electricity necessary to grid stability.

This Master's Project examines the effect of an aggressive build out of intermittent renewables on Germany's wholesale electricity market. The recent decline in wholesale electricity prices and numerous negative electricity price events have indicated that the build out of renewables has impacted electricity markets substantially in recent years (Economist, 2013). This analysis seeks to quantify further reductions in wholesale electricity price as a result of renewables built out via the Energy Concept. The effect of these price reductions on Germany's wholesale electricity market will then enable predictions regarding the future of Germany's electricity market.

Methods

In order to evaluate the relative contribution and competitiveness of Germany's electricity generators, a cumulative supply curve was constructed. The supply curve includes the four generators types that generated the most electricity in 2013 (coal, renewables [inclusive of wind, solar, and hydro], natural gas, and nuclear). Country-wide generation capacities for 2013 were collected from a Fraunhofer Institute report (Fraunhofer Institute, 2013). Marginal cost data and generator-specific capacity factors for Germany were obtained from the International Energy Agency's *Projected Costs of Generating Electricity* (IEA, 2010). Marginal costs were calculated by subtracting investment costs from total levelized costs of electricity (LCOE). Renewables were deemed to have a 0 €/MWh marginal cost to reflect the 0 €/MWh fuel cost and the fact that renewables are given dispatch priority by grid operators. To illustrate the impact of intermittent renewables on the cumulative supply curve, three curves were constructed. Using hourly generation datasets described below, the three curves represent Germany's cumulative

generation supply when intermittent renewables were at their minimum activity, average activity, and maximum activity, based on total generation for a calendar day.

The interaction between observed wholesale electricity price and observed total generation (which is a proxy for total demand, excepting international electricity imports and exports) was evaluated to determine any significant trends that exist in the relationship between price and demand as the activity of intermittent renewables varies. Price data were obtained from the European Power Exchange (EPEX, 2014b). The selected dataset included hourly spot prices on the day-ahead wholesale market, for every hour in 2013. This dataset represented the most recent full calendar year, providing a sufficiently large sample set across all four seasons. The corresponding demand dataset was also representative of hourly demand for every hour in 2013 (EEX, 2014). Summing hourly generation observed for conventional ($\geq 100\text{MW}$), wind, and solar generators in Germany was used as a proxy for nationwide demand (EEX, 2014). Contribution of renewables to total demand was calculated by adding generation from solar and wind and dividing that sum by total demand.

To quantify the relationship between generation from renewables and wholesale electricity prices, regressions were run using the aforementioned price and demand datasets (EPEX, 2014b; EEX, 2014). The first iteration was a linear regression using percentage of electricity generated by renewables to explain electricity price. The second iteration used the same explanatory and dependent variables, but included dummy variables to control for time of day (morning [7 a.m. – 10 a.m.], midday [11:00 a.m. – 1:00 p.m.], afternoon [2:00 p.m. – 5:00 p.m.], evening [6:00 p.m. – 9:00 p.m.], night [10:00 p.m. – 6:00 a.m.]), season (spring [March, April, May], summer [June, July, August], fall [September, October, November], winter [December, January, February]), and day of week (weekend, weekday).

Finally, to quantify the effect to total wholesale generator revenue, a normal distribution was fitted to a histogram of 2013 hourly electricity prices (EPEX, 2014b). The price distribution was then shifted according to the results from the regression analysis. To quantify the total revenue loss to the wholesale generator market, the area under the shifted normal distribution was subtracted from the area under the original normal distribution. The difference was then multiplied by annual demand (2013 demand was used to maintain a conservative estimate) to forecast the total loss in revenue resulting from an increase in generation supplied by renewables (EEX, 2014). The relative effect of this revenue loss on each generator type was evaluated by comparing generator-specific marginal costs to the original and shifted wholesale price probability distribution functions. This method allowed for the comparison of current and future dispatch likelihood for each type of generator.

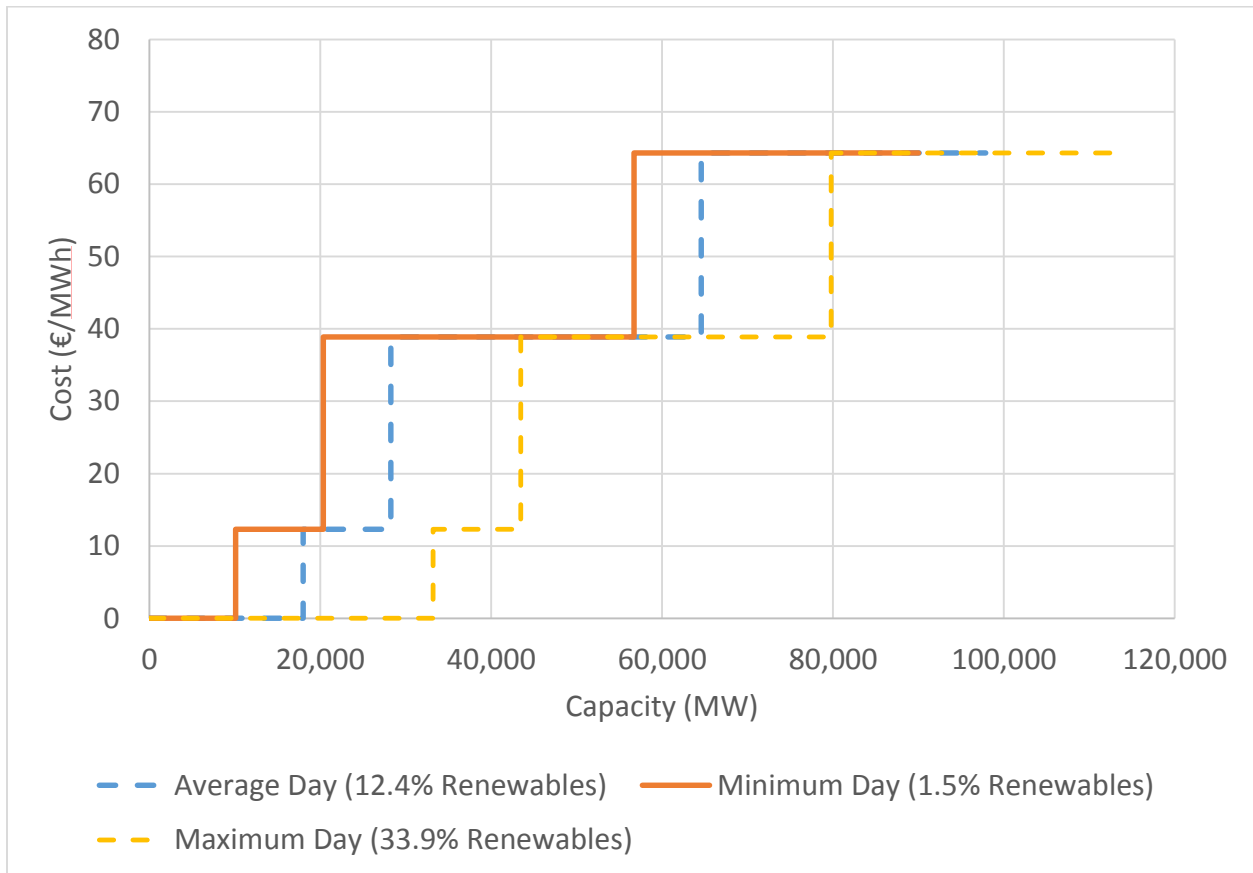
Results

The cumulative supply curve representing Germany's hourly generation capacity demonstrates the differences between each electricity generator type in Germany's portfolio. In order of ascending marginal cost, renewables are the cheapest source of electricity (0 €/MWh), followed by nuclear (12.3 €/MWh), coal (38.9 €/MWh), and natural gas (64.3 €/MWh) (Figure 1; IEA, 2010). The effect of intermittent renewables explains the difference between the three curves. As the activity of intermittent renewables increases, the capacity of the renewables segment increases, which subsequently shifts out the total capacity of the supply curve.

Plotting hourly demand against wholesale electricity price reveals trends relating to the activity of intermittent renewables (EPEX, 2014b; EEX, 2014). For example, as the activity of renewables increases from generating <10% of electricity to >40% electricity, the price curve

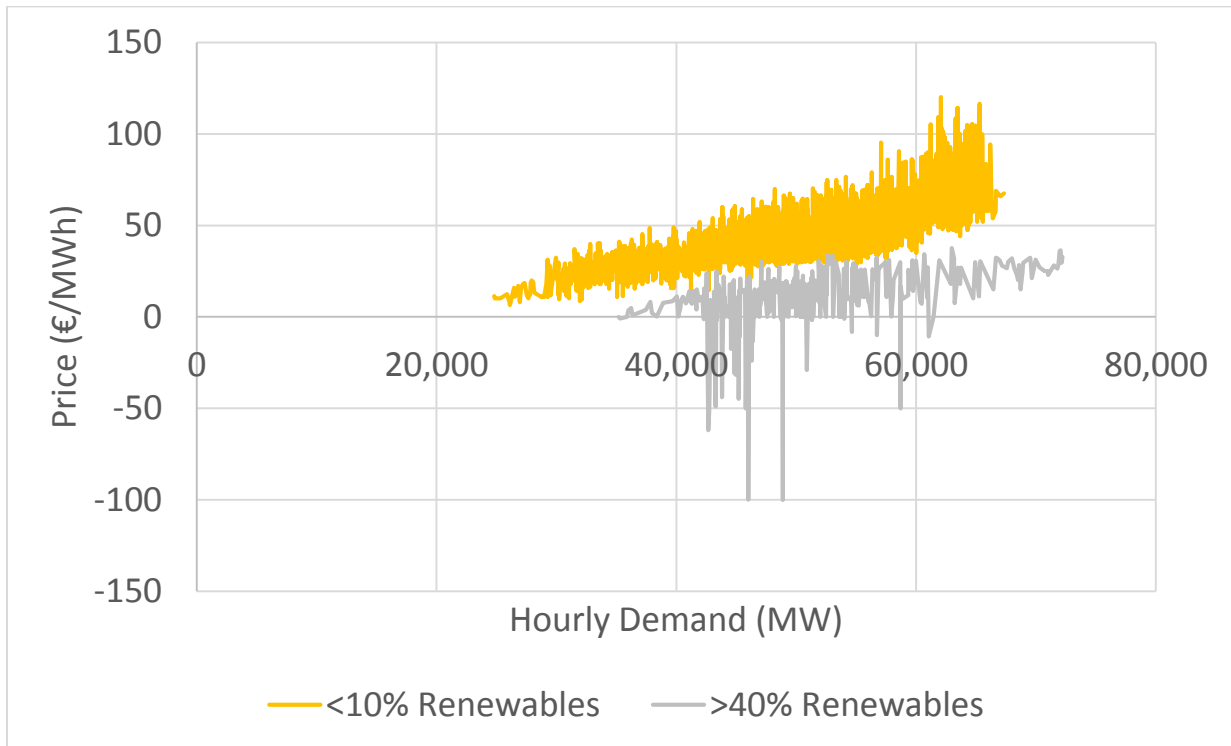
shifts downward (Figure 2). This shift demonstrates that additional electricity generated by intermittent renewables decreases wholesale electricity price for any given amount of demand.

Figure 1. Cumulative Supply Curve.



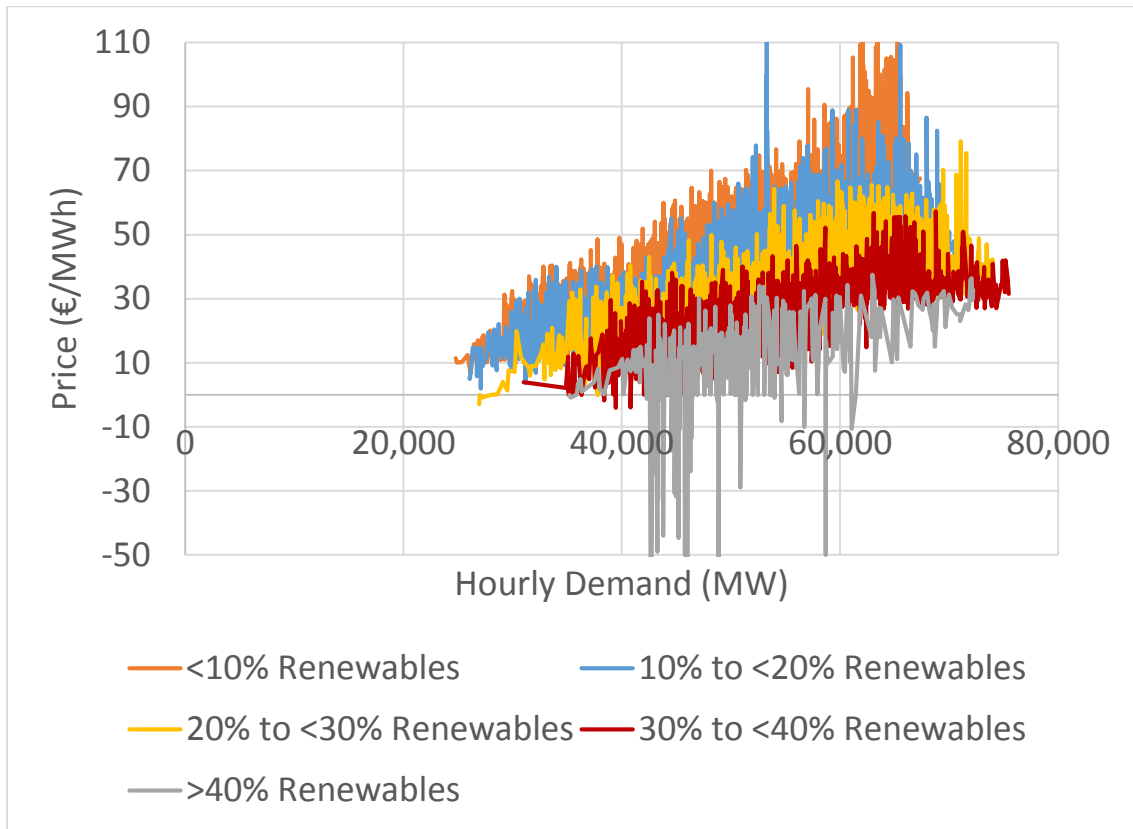
In addition to the two series represented in Figure 2 (<10% renewables and >40% renewables), the intermediate range of generation from renewables (10% to 40%) follows the same trend. For each incremental increase in the amount of electricity supplied by renewables, the price curve shifts downward (Figure 3; EPEX, 2014b; EEX, 2014).

Figure 2. Wholesale Electricity Price vs. Hourly Demand.



The occurrence of negative wholesale electricity prices also correlates with the activity of intermittent renewables. In 2013, the percentage of hours with negative wholesale electricity prices increased as the amount of electricity from intermittent renewables increased: 0.00% of hours with <10% renewables; 0.00% of hours with 10% to <20% renewables; 0.25% of hours with 20% to <30% renewables; 0.82% of hours with 30% to <40% renewables; and 14.57% of hours with $\geq 40\%$ renewables. In line with these two trends associated with increasing activity from intermittent renewables (downward price shift and increase in negative prices), the magnitude of negative prices increases as well. The average of the negative hourly prices for 20% to <30% renewables is -0.97 €/MWh. For 30% to <40% renewables, the average is -1.24 €/MWh. For $\geq 40\%$ renewables, the average is -17.17 €/MWh.

Figure 3. Wholesale Electricity Price vs. Hourly Demand for Every Hour in 2013.



Two regressions were run in order to quantify the impact of the percentage of electricity supplied by renewables on wholesale electricity price (EPEX, 2014b; EEX, 2014). In the case of the simple regression, the explanatory variable, “percentage of generation provided by renewables,” explained 21% of the trend observed in price (adjusted $R^2 = 0.215$) (Figure 4). The intercept and explanatory variable coefficient were highly statistically significant ($p < 0.001$; $p < 0.001$, respectively) (Table 1). This regression indicated that a 10% increase in the amount of electricity supplied by renewables will yield a decrease in average wholesale electricity price of 6.5 €/MWh.

Figure 4. Percentage of Generation Provided by Renewables vs. Wholesale Electricity Price.

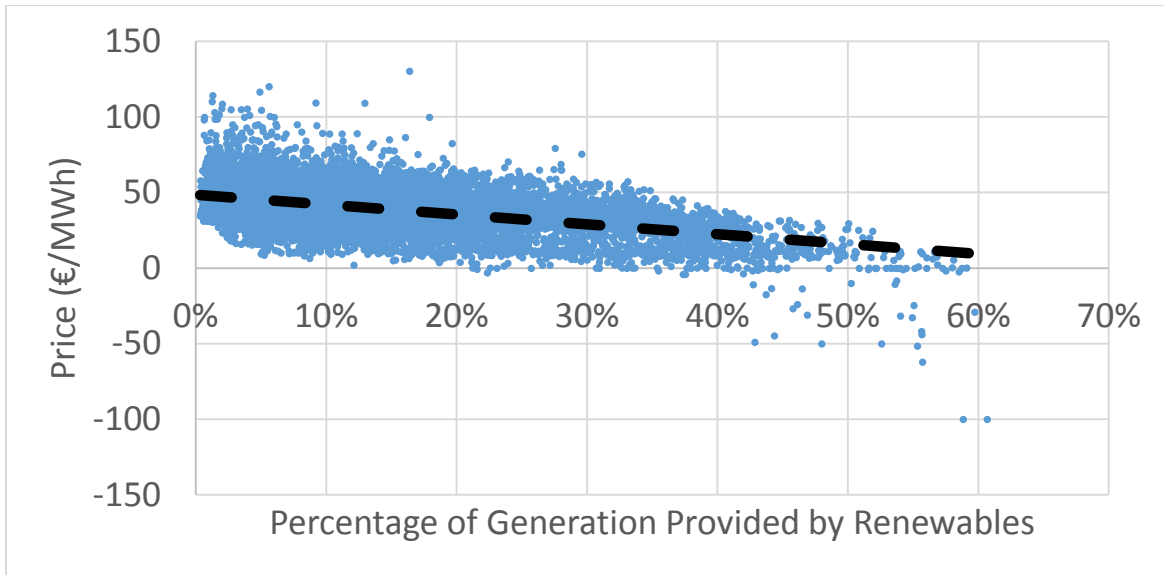


Table 1. Simple Regression Summary (Renewables vs. Price).

Regression Statistics: Simple Regression for Price (1 variable, n=8760)						
	R-Squared	Adj.RSq	Std.Err.Reg.	# Cases	# Missing (2.50%,8758)	Conf. level
	0.215	0.215	14.589	8760	0	1.960
Variable	Coefficient	Std.Err.	t-Stat.	P-value		
Intercept	48.501	0.269	180.369	0.000		
Renewables	-65.254	1.333	-48.940	0.000		

To expand upon the simple regression, a second regression was run that included 8 dummy variables (EPEX, 2014b; EEX, 2014). The dummy variables were used to control for any trends in electricity price that resulted from season, time of day, or day of the week. In this multiple regression, the same explanatory variable, “percentage of generation provided by renewables,” explained 65% of the trend observed in price (adjusted $R^2 = 0.649$). Again, the renewables explanatory variable coefficient was highly statistically significant ($p < 0.001$), as were the intercept and the coefficient for all dummy variables (Table 2). This regression

indicated that a 10% increase in the amount of electricity supplied by renewables will yield a decrease in average electricity price of 8.5 €/MWh.

Table 2. Multiple Regression Summary (Renewables vs. Price).

Regression Statistics: Multiple Regression for Price (9 variables, n=8760)						
	R-Squared	Adj.RSq	Std.Err.Reg.	# Cases	# Missing (2.50%,8750)	Conf. level
	0.650	0.649	9.751	8760	0	1.960 95.0%
Variable	Coefficient	Std.Err.	t-Stat.	P-value		
Intercept	60.159	0.332	181.275	0.000		
Afternoon	1.669	0.374	4.468	0.000		
Midday	5.542	0.424	13.059	0.000		
Morning	5.715	0.373	15.312	0.000		
Night	-17.140	0.307	-55.832	0.000		
Renewables	-85.391	1.043	-81.883	0.000		
Spring	-1.969	0.295	-6.681	0.000		
Summer	-2.417	0.296	-8.161	0.000		
Winter	0.845	0.296	2.856	0.004		
Wkend?	-10.348	0.236	-43.912	0.000		

To quantify the effect of a price shift on wholesale generators, the price probability distribution function (PDF) that was fitted to a histogram of 2013 electricity prices (Figure 5) was then shifted downward to represent the effect of increasing from 25% to 35% renewables (EPEX, 2014b). Shifts of 8.5 €/MWh (best guess scenario) and 6.5 €/MWh (conservative scenario) were compared to the current scenario (Figure 6). By subtracting the area under the shifted curve from the area under the current scenario curve and multiplying by current annual demand (456 TWh), the estimated annual revenue loss ranges from €2.96 billion for the conservative scenario to €3.88 billion for the best guess scenario (EEX, 2014). These figures represent a loss in annual revenue ranging from 17.7% to 23.2%, respectively (EPEX, 2014b; EEX, 2014).

Figure 5. 2013 Wholesale Electricity Prices – Histogram and Normal PDF.

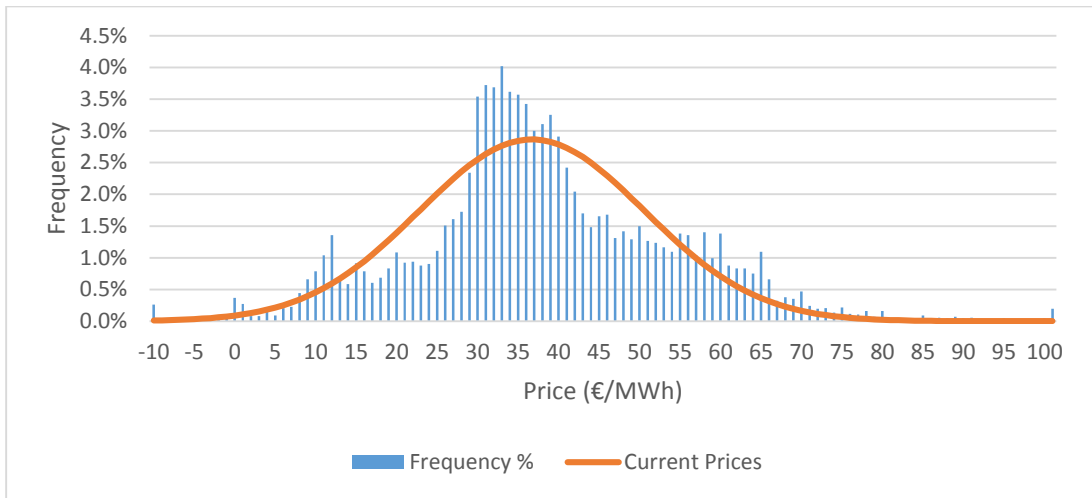
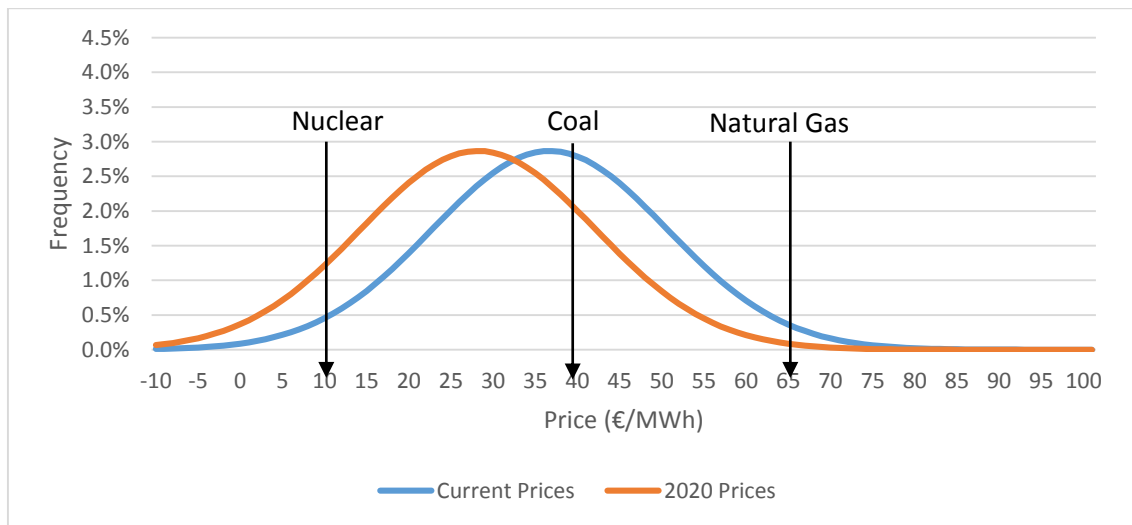


Figure 6. Current Price PDF vs. 2020 Price PDF with Generator-Specific Marginal Costs.



By comparing the marginal cost of each generator type to the upper-tail of the current and 2020 price distributions, the likelihood of profitable dispatch was determined (Table 3). As wholesale electricity prices decrease, the generators with higher marginal costs have their likelihood of dispatch decreased by a greater percentage.

Table 3. Comparison of Dispatch Probability Following 2020 Wholesale Price Decrease.

	<i>Marginal Cost</i>	<i>Current Dispatch Probability</i>	<i>2020 dispatch probability</i>	<i>Decrease in dispatch probability</i>
<i>Renewables</i>	0	N/A (always dispatched due to grid priority)		
<i>Nuclear</i>	12.33	96.0%	87.3%	9.1%
<i>Coal</i>	38.87	43.8%	22.2%	49.4%
<i>Natural Gas</i>	64.31	2.4%	0.5%	80.0%

Discussion

As demonstrated by the price shifts observed in Figures 2, 3, and 4, empirical 2013 price data demonstrates that average wholesale electricity prices decrease as the amount of electricity supplied by renewables increases (EPEX, 2014b; EEX, 2014). The three curves displayed in the cumulative supply curve highlight the reason for this shift – because renewables are always used due to their grid priority, they sit at the base of the cumulative supply curve (Figure 1).

Therefore, as their total capacity and production increases, the entire supply curve is shifted outward, leading to additional generation capacity that can be produced at a lower marginal cost.

These reductions in wholesale electricity price directly impact generators who sell into the wholesale electricity market. In order to understand the magnitude of the impact felt by these generators, it is important to quantify the price shift that will result from the increased build out of renewables. The results from the regressions (Figure 4; Table 1; Table 2) suggest that the impact felt by wholesale generators by 2020 will be significant. As the amount of electricity supplied by renewables increases by 10% (from 25% to 35%), the subsequent decrease in wholesale electricity price of 6.5 €/MWh to 8.5 €/MWh will have a significant impact on the economics of market players. Not only will this price decrease result in an annual loss of revenue ranging from €2.96 billion to €3.88 billion (17.7% to 23.2% of annual revenue, respectively), but it will not impact all generator types equally.

Plants with higher marginal costs will be adversely affected more than plants with cheaper marginal costs. This disproportionate effect is tied to the likelihood of dispatch that can be predicted based on the comparison of marginal cost to wholesale electricity price. In order for a plant to generate profitably, the wholesale price of electricity must exceed the marginal cost to generate (with some exceptions relating to start-up and shut-down costs). Therefore, by lowering the average price of an approximately normal price distribution, plants with higher marginal cost will be able to dispatch disproportionately less than plants with cheaper cost structures. This uneven decrease in profitable dispatch is highlighted in Table 3 – natural gas plants are 80.0% less likely to dispatch, compared to a 49.4% reduction for coal plants and a 9.1% reduction for nuclear plants.

As natural gas plants are forced to dispatch less frequently, many will be forced to shut down. Power plants, such as natural gas plants, require a huge capital expense when they are first built. In order for the plant to be profitable to investors, the plant must meet certain capacity factors specified in the assumptions made during planning and construction (Peppiatt, 1995). Because the dispatch likelihood of natural gas plants will decrease substantially, the capacity factor goals will not be met, and many plants will be phased out to prevent further losses. Another factor that will contribute to the loss of natural gas plants is the negative price events that have become increasingly common in recent years. Negative prices serve as a signaling mechanism to fast-ramping plants (e.g., natural gas plants) to go offline (EPEX, 2014a). Plants with more cumbersome ramping procedures and costs (e.g., nuclear plants) are better off paying money to continue generating electricity than they are incurring the costs of shutting down and ramping back up (EPEX, 2014a).

Phasing out of natural gas plants can have a substantial impact on Germany's electricity market as a whole. One notable effect relates to the loss of fast-ramping electricity. Natural gas plants, which have relatively fast ramp rates, synergize well with intermittent renewables (IEA, 2013). Because Germany is continuing to build out intermittent renewables, the total volatility of generation will increase over time. Therefore, fast-ramping electricity resources become even more essential to maintaining grid stability. If natural gas plants are phased out, grid stability could be compromised and Germany will have to use creative infrastructure to prevent an increase in outage events.

Additionally, as a result of a decrease in natural gas plants and capacity, Germany will continue to be reliant on coal. In 2013, 45.2% of electricity was generated from coal resources. As discussed earlier, the build out of renewables will replace natural gas plants – therefore, coal plants will continue to be relied upon. Additionally, coal capacity will likely have to increase to compensate for a decrease in generation from nuclear plants as the remaining 9 nuclear plants are decommissioned by 2022 (Economist, 2013). This increased reliance on coal will prevent Germany from reducing its carbon emissions, thereby negating a positive effect of increased renewables.

The findings of the Master's Project can readily be transferred to other countries or regions that are emulating Germany's aggressive push for electricity supplied by renewables. A number of European countries (e.g., Spain, Denmark) and U.S. states (e.g., California) have built out substantial renewable resources and will continue to pursue their own renewable portfolio standards (EIA, 2013; Energinet, 2013; CEC, 2014). Similar to Germany, as the total capacity of intermittent renewables increases, so too will the generation volatility due to natural fluctuations in production. Also, most grid operators give priority to renewables, which means that they

always comprise the base segment of the supply curve (Figure 1). As a result, universal to every location, an increase in intermittent renewables, holding all else equal, will over time decrease wholesale electricity prices because of the interplay between supply and demand.

For locations with an electricity generation portfolio similar to Germany and feed-in tariffs that are financed by ratepayer surcharges, the aforementioned impacts to Germany's electricity grid would be expected to occur. There will be a disconnect in the prices paid by retail customers and the prices received by wholesale generators due to the ratepayer surcharge. This allows for rising retail prices concurrent with dropping wholesale prices. As a result, both ratepayers and wholesale generators are expected to become disenchanted with the methods behind supporting the build out of renewables. As evidenced in Germany, many citizens and organizations that originally supported aggressive renewables build out began advocating for a rework of the Energy Concept (DW, 2013). Political support for a reduction in both the ratepayer surcharge and the originally stated renewables targets (35% of electricity by 2020; 80% of electricity by 2050) has increased significantly in recent years (Euractiv, 2014).

As other locations approach penetration of intermittent renewables equal to Germany, they should prepare for similar challenges and opposition, or attempt to mitigate them by adopting a slower rate of increased renewables penetration and a correspondingly smaller ratepayer surcharge. As wholesale electricity prices decrease over time, generators with higher marginal costs will be disproportionately affected, as previously discussed in this study (Table 3). For much of Europe, the marginal costs for natural gas plants are notably higher than for coal plants (IEA, 2010). Therefore, much like in Germany, the probability of profitable dispatch will decrease significantly for high-cost plants, making them less competitive within electricity markets. As a result, natural gas plants throughout Europe will be at risk of phase out, barring

any significant reduction in cost structure, such as LNG imports from gas-rich countries like the United States (Cunningham, 2014).

In contrast to Europe, the effect of an aggressive build out of renewables will likely take a different course. Although renewables penetration will cause a decrease in wholesale electricity prices and an increase in retail prices through financing of feed-in tariffs and other subsidies, the United States benefits from an abundance of natural gas. Due to the excess availability of natural gas extracted from shale rock, natural gas prices in the United States are much lower than they are in Europe (EIA, 2014b). These lower fuel prices translate into a different marginal cost structure relative to Europe. After converting currencies, in the United States, marginal costs are as follows: 15.01 €/MWh for nuclear, 37.12 €/MWh for coal, and 52.14 €/MWh for natural gas (IEA, 2010). Marginal costs for coal are very similar to those demonstrated in Germany (-4.5%); although costs for nuclear are much higher in the United States (+21.7%), Germany's phase-out of nuclear plants makes a comparison of the competitiveness of nuclear generators irrelevant; the notable difference in cost structure is that costs for natural gas plants are much lower in the United States than in Germany (-18.9%) (IEA, 2010). Unlike the commodity coal, natural gas is very costly to ship overseas due to the liquefying process (National Geographic, 2014). Therefore, natural gas prices do not equilibrate internationally to the same degree as coal prices (Charles River Associates, 2014). Because the relative marginal costs of coal and natural gas generators in the United States are much more similar than in Germany, natural gas plants will not be put at a significant disadvantage in terms of reaching target capacity factors (IEA, 2010). Instead, it is likely that the more expensive coal plants and natural gas plants will suffer relative to more efficient and cheaper competitor plants, regardless of fuel type. This is beneficial from an overall market perspective because coal plants will not automatically out-compete natural gas

plants due to their marginal costs. Natural gas plants can remain more competitive and continue to provide services that coal plants cannot – fast ramp-rates and lower carbon emissions (IEA, 2013).

As a result of these market dynamics, locations such as Germany will experience either constant or increasing carbon emissions, while places such as California will be able to reduce their carbon emissions over time. The important distinction between these two locations is that in Germany, some of the electricity production formerly from natural gas plants will be replaced by coal plants. This replacement is ultimately a result of the higher marginal cost of natural gas plants and the reduced ability of natural gas plants to dispatch profitably in conjunction with decreasing wholesale electricity prices (Figure 6; Table 3). Because the marginal costs for natural gas plants and coal plants in California are much closer to parity, efficient natural gas plants will still be able to compete as wholesale electricity prices drop due to increased penetration of intermittent renewables. Because natural gas plants can emit as little as 44% of the CO₂ produced by coal plants, keeping a significant amount of natural gas plants in its generation portfolio will better enable California to minimize its impact on climate change (Gouw, 2014).

In addition to the climate-related impacts, the effect of intermittent renewables on Germany's electricity market brings into question the usefulness of subsidy instruments such as feed-in tariffs funded through ratepayer surcharges. Although feed-in tariffs spur growth of renewables by providing relatively riskless future cash flows, it might prove beneficial to reduce the length over which these subsidies are provided (GTM, 2010). If Germany had allowed its substantial feed-in tariffs to expire earlier, then retail electricity rates might have risen less and specific generator types (natural gas) would not have been put at a competitive disadvantage. The downside associated with abandoning these feed-in tariffs earlier would be a slower

adoption of renewables, and less ambitious electricity portfolio targets. But for locations attempting to learn from Germany's experiences, a less aggressive build out of intermittent renewables may provide a significant benefit via less disruption to existing electricity markets.

Literary Citations

- BMU. 2010. "Energy Concept for an Environmentally Sound, Reliable, and Affordable Energy Supply." Retrieved from http://www.germany.info/contentblob/3043402/Daten/1097719/BMUBMWi_Energy_Concept_DD.pdf.
- California Energy Commission. 2014. "California Electricity Statistics & Data." Retrieved from <http://energyalmanac.ca.gov/electricity/>.
- Charles River Associates. 2014. "Evaluation of the 2014 Annual Energy Outlook Early Release: Implications for U.S. LNG Exports and Natural Gas Prices." Retrieved from <http://democrats.energycommerce.house.gov/sites/default/files/documents/Report-Charles-River-Associates-2014-Energy-Outlook-Release-2013-2-3.pdf>.
- Cunningham, N. 2014. "Can U.S. LNG Break Russia's Gas Grip on Europe?" *OilPrice.com*. Retrieved from <http://oilprice.com/Energy/Natural-Gas/Can-U.S.-LNG-Break-Russias-Gas-Grip-on-Europe.html>.
- DW. 2013. "German Households to be Hit by Higher Electricity Surcharge." Retrieved from <http://www.dw.de/german-households-to-be-hit-by-higher-electricity-surcharge/a-17157987>.
- The Economist. 2013. "How to Lose Half a Trillion Euros." Retrieved from <http://www.economist.com/news/briefing/21587782-europes-electricity-providers-face-existential-threat-how-lose-half-trillion-euros>.
- Energinet. 2013. "Environmental Report for Danish Electricity and CHP." Retrieved from <https://www.energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Klimaogmiljo/Environmental%20report%20for%20Danish%20electricity%20and%20CHP%20-%20summary%20of%20the%20status%20year%202012.pdf>.

Energy Information Administration (EIA). 2013. "Overview Data for Spain." Retrieved from <http://www.eia.gov/countries/country-data.cfm?fips=SP&trk=m>.

Energy Information Administration (EIA). 2014a. "Electric Power Monthly." Retrieved from http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

Energy Information Administration (EIA). 2014b. "Market Trends – Natural Gas." Retrieved from http://www.eia.gov/forecasts/aeo/MT_naturalgas.cfm.

Euractiv. 2013. "German Energy Prices 50% Higher than EU Average: McKinsey." Retrieved from <http://www.euractiv.com/sections/energy/german-energy-prices-50-higher-eu-average-mckinsey-269844>.

European Energy Exchange (EEX). 2014. "EEX Transparency Platform." Retrieved from <http://www.transparency.eex.com/en/>.

European Power Exchange (EPEX). 2014a. "Negative Prices: Q&A." Retrieved from http://www.epexspot.com/en/company-info/basics_of_the_power_market/negative_prices.

European Power Exchange (EPEX). 2014b. "EPEX Spot Auction." Retrieved from <http://www.epexspot.com/en/market-data/auction/auction-table/2013-01-01/DE>.

Eurostat. 2013. "Electricity and Natural Gas Price Statistics." Retrieved from http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Electricity_and_natural_gas_price_statistics.

Federal Statistical Office of Germany. 2014. "Gross Electricity Generation in Germany for 2011-2013." Retrieved from <https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/Energie/Erzeugung/Tabellen/Bruttostromerzeugung.html;jsessionid=11A259FCCDA16354BDCC19151DAFBACD.cae1>.

Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer Institute). 2013. "Electricity Spot-Prices and Production Data in Germany 2013." Retrieved from <http://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/news/electricity-prices-and-production-data-2013.pdf>.

German Energy Agency (DENA). 2012. "Hydropower – Current Facts and Figures." Retrieved from <http://www.renewables-made-in-germany.com/en/renewables-made-in-germany-start/hydropower/hydropower/market-development.html>.

German Missions in the United States (Germany.info). 2012. "Key Messages on German Climate and Energy Policy." Retrieved from http://www.germany.info/Vertretung/usa/en/06__Foreign__Policy__State/02__Foreign__Policy/05__KeyPoints/ClimateEnergy__Key.html.

Germany Trade and Invest (GTAI). 2014. "Germany's Energy Concept." Retrieved from <http://www.gtai.de/GTAI/Navigation/EN/Invest/Industries/Smarter-business/Smart-energy/germanys-energy-concept,did=383282.html>.

Gouw, J., Parrish, D., Frost, G., and Trainer, M. 2014. "Reduced Emissions of CO₂, NO_x, and SO₂ from U.S. Power Plants Due to the Switch from Coal and Natural Gas with Combined Cycle Technology." Retrieved from <http://s3.amazonaws.com/windaction/attachments/2065/ReducedEmissions-US-PowerPlants.pdf>.

GreenTechMedia (GTM). 2010. "Feed-In Tariffs Can Spur Disruptive Growth." Retrieved from <http://www.greentechmedia.com/articles/read/feed-in-tariffs-spurs-disruptive-growth>.

Held, A., Ragwitz, M., Huber, C., Resch, G., Faber, T., and Vertin, K. 2007. "Feed-In Systems in Germany, Spain, and Slovenia: A Comparison." Retrieved from <http://www.mresearch.com/pdfs/docket4185/NG11/doc44.pdf>.

International Energy Agency (IEA). 2010. "Projected Costs of Generating Electricity." Retrieved from http://www.iea.org/publications/freepublications/publication/projected_costs.pdf.

International Energy Agency (IEA). 2013. "Gas to Coal Competition in the U.S. Power Sector." Retrieved from http://www.iea.org/publications/insights/CoalvsGas_FINAL_WEB.pdf.

Meza, E. 2013. "EU Targets Germany Renewable Energy Act." *PV Magazine*. Retrieved from http://www.pv-magazine.com/news/details/beitrag/eu-targets-german-renewable-energy-act_100012046/#axzz2bzmlHJoA.

National Geographic. 2014. "North American Natural Gas Seeks Markets Overseas." Retrieved from <http://news.nationalgeographic.com/news/energy/2014/03/140320-north-american-natural-gas-seeks-markets-overseas/>.

Peppiatt, S. 1995. "Introduction to Power Station Project Financing." *International Tax & Business Law* (46). Retrieved from <http://scholarship.law.berkeley.edu/bjil/vol13/iss1/2>.

Post, W. 2011. "German Nuclear Decommissioning and Renewables Build-Out." *The Energy Collective*. Retrieved from <http://theenergycollective.com/willem-post/67528/german-nuclear-decommissioning-and-renewables-build-out>.