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PRICE RISK, PRODUCTION FLEXIBILITY, AND LIQUIDITY MANAGEMENT: EVIDENCE FROM ELECTRICITY GENERATING FIRMS

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Price Risk, Production Flexibility, and Liquidity Management: Evidence from Electricity Generating Firms
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ABSTRACT

Production inflexibility together with product price uncertainty creates price risk, which is a potentially important factor for firms' liquidity management. One industry for which price risk can be measured is the electricity producing industry. We use data on hourly electricity prices in 41 markets to measure fluctuations in output prices and information on over 60,000 power plants to approximate firms' flexibilty to vary output quantities. Our results suggest that higher electricity price volatility leads to increased cash holdings, but only in firms using inflexible production technologies. This effect is robust to a number of specification choices including instrumenting for volatility in electricity prices using weather forecast data. After deregulation, firms hold 20-25% more cash, suggesting that the process of deregulation increases the risk firms' face. Price risk affects cash holdings most in financially constrained firms, and in firms that cannot easily hedge the electricity price through derivative markets. Capital market liquidity and balance sheet liquidity appear to be substitutes for one another.

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> Moody's Investors Service says that power prices are expected to remain volatile […] Individual generators that can rapidly adjust their output in response to price swings will likely benefit, but those that cannot could prove commercially unviable over time.
>
> *Moody's Investor Service (2016)*

1. Introduction

One source of risk facing many firms is price risk. Price risk occurs when firms with inflexible production face uncertainty about the market price of their products. For instance, if firms must decide on the production volume before knowing the exact demand for their product, they will face costs when they have to alter production. The magnitude of these costs depends on the nature of the production process: the more inflexible the production process is, the higher the *ex post* cost of altering production and hence the higher the *ex ante* price risk.[1] For this reason, price risk can potentially be an important factor in firms' liquidity management decisions.

An industry for which price risk is both relevant and empirically measurable is the electricity generating industry. In many parts of the world, this industry has been deregulated. In deregulated electricity markets, electricity producers sell their product on a wholesale market to electricity retail firms, who then distribute it to the consumers. Because generation capacities are fixed in the short-run, wholesale prices fluctuate considerably when demand for electricity changes, which often occurs because of changes in weather or seasonal factors. Since storing electricity is prohibitively expensive, electricity prices tend to fluctuate much more than prices in other commodity or financial markets. Consequently, generating firms have to adjust production in response to demand changes, which often entails the shutdown and later restart of plants. Depending on the method used to produce electricity, shutdowns and restarts of plants can take considerable time, and such disruptions to production can be very costly for producers. For this reason, price fluctuations and the associated uncertainty create risk for energy utilities, especially those using inflexible production technologies such as coal-fired power plants.

[1] Discussion of price risk dates to the classic paper by Sandmo (1971), and the idea that flexibility in production affects its magnitude comes from Turnovsky (1973) and Epstein (1978).

This paper measures the extent to which price risk affects the liquidity management decisions of electricity producing companies. It considers a sample of 481 electricity-generating firms between 1999 and 2014. These firms operate more than 60,000 individual plants, which use technologies ranging from wind power to coal to nuclear power, and represent the vast majority of publicly traded electricity generating firms in the world. In most of our empirical tests, we focus on the 253 firms that sell electricity in organized markets in which retail firms purchase electricity from the wholesale market. In 41 regional markets from 30 countries, we are able to obtain the hourly wholesale prices received by our sample firms during our sample period.[2]

However, price uncertainty is unlikely to create the same price risk for all electricity producing firms. Rather, their production technology is likely to play a key role. Using data on firms' power plants to approximate how easy the can adjust production to changing prices, we analyze whether firms' liquidity choices vary systematically with the price risk they face. Firms which operate flexible plants such as gas-fired plants can quickly shut down these plants as soon as the price falls below their variable cost. For less flexible plants like coal this is more difficult as the shut-down and restart typically requires several hours and involves considerable cost.[3] To measure price uncertainty, we use data on hourly electricity wholesale prices in a power market. These data allow us to estimate a firm's price risk because electricity producers sell most of the electricity in the market where the plant is located.[4] Hourly prices are used instead of daily or weekly prices because power plants are dispatched *within* a day. For instance, gas-fired power plants would be turned on as soon as the price increases above their marginal cost. Daily prices average all hourly prices of a day and are thus less precise.[5] Based on these hourly prices, we

[2] These are virtually all markets around the globe that operate a day-ahead market for electricity and have hourly pricing. Section 2.1 provides an overview on the markets and the criteria for their inclusion.
[3] Instead of shutting down a plant, the operator could also reduce its load. However, there are considerable technical limitations to this approach. For instance, operators of gas combined cycle and coal-fired power plants typically limit the minimum generation to about 40% to 50% of its capacity. Furthermore, the efficiency of thermal power plants decreases significantly for low load levels.
[4] Selling in electricity to other markets is possible, but there are substantial technical (e.g., losses due to transmission) and legal (e.g., market regulations) limitations. Based on geographical segment data, we estimate that our sample firms sell more than 90% of their production in the market where they are located.
[5] For instance, consider a daily average electricity price of 50 USD/MWh and a gas-fired power plant with variable cost of 75 USD/MWh. To know whether this plant was switched on or not, it is necessary to know the distribution of

calculate the electricity price volatility during a firm's fiscal year. We use the average volatility during the whole fiscal year because cash holding decisions are typically not made on short-term (e.g., daily or weekly) basis. We focus on firms' cash holdings, since they are the most common way that firms adjust the liquidity of their balance sheet. Because of the many institutional, tax, and cultural differences across countries and markets, we include firm fixed effects in all equations we report, so that the results should be interpreted as the way in which a particular firm changes its cash holdings in response to changes in market conditions.

Our estimates suggest that firms with inflexible production do adjust their cash holdings in response to changes in price uncertainty. For firms using relatively flexible technologies such as gas-fired power plants, in which output can be adjusted very quickly and at little or low cost, we find little effect of price uncertainty on liquidity management. However, firms using inflexible production technologies such as coal react to changes in the volatility of wholesale prices changing the amount of cash they hold. These findings suggest that firms do hedge price risk through liquidity management.

To isolate the channel through which price risk affects liquidity decisions, we rely on the fact that electricity prices are heavily influenced by an exogenous factor – the weather. While electricity capacity is rather fixed in the short-run and supply can be planned by energy utilities, electricity demand varies considerably. One important determinant of electricity demand is the weather (Perez-Gonzalez and Yun, 2013).[6] Since adjustments in the electricity supply are costly and slow, demand changes due to unexpectedly high or low temperatures lead to price fluctuations. We approximate such unexpected weather events by deviations of actual temperatures from forecasted values, which lead to unexpected

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hourly prices within the day. For a price of 50 USD/MWh for all hours, the plant would not run; for a price of 100 USD/MWh during 12 hours and 0 USD/MWh during the other 12 hours, the plant would run 50% of the time. Similarly, consider a coal plant with variable cost of 30 USD/MWh. In the first scenario, this plant would be highly profitable. However, in the second scenario, the plant would likely also produce despite a price below marginal cost, which reduces its overall profitability.

[6] In this context, Vattenfall, a large European energy utility, states that "[e]lectricity prices on the Nordic electricity exchange, Nordpool, are 70 per cent governed by the elements." (http://corporate.vattenfall.com/news-and-media/news/2014/how-the-weather-affects-the-electricity-price/)

demand and increase the volatility of electricity prices.[7] Using this logic, we construct an instrument for electricity price volatility based on how uncertain (or unpredictable) future temperatures are in a power market and year. This instrument varies considerably between different regions and over time.[8] Instrumenting for volatility using this approach leads to similar findings to those discussed above: price uncertainty increases cash holdings of firms with inflexible production technologies but not those with flexible production technologies.

We perform a number of robustness tests to ensure that these results do not occur because of arbitrary choices we have made in our empirical design. For instance, we use alternative proxies for operational adjustment cost or alternative measurements for electricity price volatility (based on annual prices). To mitigate concerns that our results are driven by a specific production technology (e.g., nuclear power plants which are special along several dimensions), we reestimate our equations excluding all firms that operate several specific technologies. To ensure that the results do not reflect the actions of energy utilities who have market power and therefore can influence wholesale electricity prices, we reestimate our equations without all firms that account for more than five or ten percent of the production capacity in any specific market. All of these tests confirm the main finding that price risk coming from volatility in wholesale prices is an important factor in electricity producing firms' liquidity management decisions.

As originally argued by Keynes (1936), holding cash for precautionary reasons only makes sense if there is some likelihood of a firm facing financial constraints in the future. Holding cash is costly for a number of reasons, so if a firm can always borrow costlessly at the appropriate cost of capital, reliance on the capital market should dominate holding cash. Therefore, we expect that if the results we present occur because of firms hedging price risk by holding cash on their balance sheets, the effect should be larger for firms likely facing financial constraints.

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[7] Ronald N. Keener, Senior Scientist of Duke Power Company states in this context that a "conservative annual estimate of weather error costs associated with startup-shutdown of generation units is $8,000,000 for Duke Power." (http://sciencepolicy.colorado.edu/socasp/weather1/keener.html)

[8] For time series variation, two effects are important. First, forecasting techniques are becoming more precise over time. Second, the weather tends to be more extreme and unpredictable due to the climate change.

To evaluate this argument, we split our sample into subsamples of firms based on their production flexibility. For each sub-sample, we then estimate how financial constraints affect the way in which firms adjust their cash holdings in response to wholesale price volatility. We use four measures of financial constraints: firm size (with smaller firms being more constrained), whether the firm has participated in the syndicated loan market, whether a firm has a bond rating, and whether a firm is in a Common Law country, since these firms tend to have superior access to financing through equity markets. The estimates imply that for the subsample of firms with inflexible production, the impact of price uncertainty on cash holdings is much more pronounced in financially constrained firms. However, for the subsamples of firms that are not likely to be financially constrained, price uncertainty does not appear to affect firms' liquidity management decisions. These results suggest that, consistent with theoretical predictions, constrained firms are more prone to manage price risk through their cash positions than unconstrained firms.

An alternative way to manage price risk is to pre-sell electricity through a liquid futures market. In our sample period, the existence and liquidity of futures markets for electricity varied substantially across regions. We reestimate our equation on subsamples of firms that are in regions with liquid futures markets, and those in markets that either do not have a futures market, or have one that is relatively illiquid. Our estimates suggest that the sensitivity of cash holdings to price volatility varies inversely with the ability of firms to hedge their exposure to potential shocks through futures markets: if firms can easily hedge shocks through derivatives, even those with low production flexibility have very small changes in cash holdings following changes volatility. Since it is usually cheaper to hedge through the derivatives market than by holding cash, firms appear to do so when such markets exist and are liquid. This result highlights the way in which derivative markets are substitutes to liquidity management, and suggests that a benefit of having liquid derivative markets is that they allow firms to hold less cash on their balance sheets.

We evaluate whether firms build up liquidity reserves in response to price risk by restricting payouts. Consistent with this idea, we find that price risk leads to lower payouts, both in terms of dividends alone and also dividends plus share repurchases. Adjustments in payout policy seem to be one way in which firm using inflexible technologies achieve higher liquidity in response to price uncertainty.

Finally we consider the extent to which price risk represents a cost of deregulation to firms. Since firms hold more cash because of the wholesale price risk and holding cash is costly, the price risk electricity producers face is potentially an additional cost of deregulation. As a direct test of this idea, we compare the cash holdings of deregulated electricity producers and otherwise identical regulated ones. Consistent with the notion that deregulation increases the risk faced by electricity producers, our results suggest that firms selling on wholesale markets hold about 20-25% more cash than otherwise identical firms in regulated markets.

Our analysis extends the literature in a number of ways. First, we measure the extent to which electricity producers in deregulated markets adjust their cash holdings in response to the risk they face from wholesale price movements. While there has been prior research documenting a relation between a firm's cash flow volatility and its cash holdings, measuring this relation is challenging. Most prior literature uses accounting based measures that are only available at an annual frequency. In contrast, we rely on micro data about the output prices faced by particular producers, which leads to a clean identification of this relation. Second, the fact that we directly measure output prices rather than use firm-level cash flow data allows us to identify the impact of uncertainty on cash holdings because we can instrument for electricity price volatility by weather forecast uncertainty. Third, our detailed data on the methods of producing electricity used by different firms enables us to measure the way in which price risk depends on the inflexibility of the production process. Fourth, we use cross-firm and cross-country data to evaluate the importance of the factors that potentially influence the importance of liquidity management. In particular, we identify the way that greater access to equity and debt markets, as well as the ability to hedge in liquid futures markets are substitutes for active management of the liquidity of a firm's balance sheet. Fifth, we consider the way in which deregulation imposes risks on firms by exposing them to wholesale price movements, which lead them to have to pay costs to adjust their production decisions. We document the way in which firms compensate for this additional risk by comparing the liquidity choices of otherwise similar firms in regulated and unregulated markets.

There has, nonetheless, been a substantial literature on liquidity management. The most prominent explanation why firms hold cash dates to Keynes (1936), who originally proposed that firms hold cash as a hedge against potential future financial constraints. Opler, Pinkowitz, Stulz, and Williamson (1999) was the first paper to examine this idea empirically, and started a literature that generally concludes that the precautionary motive is an important determinant of firms' liquidity management decisions.[9]

This paper also contributes to a long line of research about the economics of energy utilities. Fabrizio, Rose and Wolfram (2007), for instance, analyze how efficiency of energy utilities is affected by regulatory changes. Furthermore, Becher, Mulherin, and Walkling (2012) investigate corporate mergers in the energy utilities industry, Perez-Gonzalez and Yun (2013) use energy utilities to disentangle the value contribution of risk management with derivatives, and Rettl, Stomper, and Zechner (2016) measure competitor inflexibility in this industry. Reinartz and Schmid (2016) analyze the impact of production flexibility on the financial leverage in the electricity-generation industry. For this purpose, they also construct flexibility measures based on the plants which are operated by firms. Reinartz and Schmid (2016) focus on the impact of flexibility on leverage, whereas this paper analyzes how price uncertainty affects cash holdings of firms with flexible and inflexible production.

This paper's analysis suggests that a cost of delivering electricity through wholesale markets is the risk that such markets expose firms to; since electricity producing firms are price takers in the wholesale market, price fluctuations create risk they must manage, either through adjustment in their cash positions or through the derivative markets.

[9] See Almeida, Campello, and Weisbach (2004), Bates, Kahle and Stulz (2009), Lins, Servaes, and Tufano (2010), Campello, Giambona, Graham and Harvey (2011), Hoberg, Phillips and, Prabhala (2014), Morellec, Nikolov and Zucchi (2014), and Erel, Jang, Minton, and Weisbach (2017). Almeida, Campello, Cunha, and Weisbach (2014) provide a survey of this literature.

2. Wholesale Price Fluctuations and Utilities' Demand for Liquidity

2.1. The Wholesale Market for Electricity

Competitive wholesale markets for electricity exist in many countries. In these markets, the prices for electricity adjust to reflect the supply and demand at a particular point in time. Consumers typically pay a pre-arranged rate to their retail company. These retail companies, however, typically purchase electricity they sell to consumers from the wholesale market at whatever the prevailing price happens to be. The suppliers of electricity on the wholesale markets are electricity-generating firms, many of which do not directly sell to final consumers. The Electricity Power Supply Association (EPSA) summarizes that "[i]n many cases, electricity is generated by a power company that ultimately will not deliver it to the end-use customer. A single megawatt […] is frequently bought and re-sold a number of times before finally being consumed. These transactions are considered "sales for re-sale," and make-up the wholesale electricity market."[10]

Wholesale markets for electricity usually have a day-ahead market (DAM) in which market participants buy and sell electricity for delivery on the following day. Thus, this market is essentially a very short-term future market. The DAM typically features contracts for the delivery of electricity during individual hours of the following day.[11] The price for electricity is formed independently for each contract and thus for every hour. Some wholesale markets also offer real-time markets in which electricity for delivery on the same day is traded. Because these markets are generally not very liquid, we focus on the DAM in which most of the trading takes place.

Wholesale electricity markets have developed in different regions of the world, with (slightly) different structures and regulations. In the U.S., the Federal Energy Regulatory Commission (FERC) order 2000, which was issued in February 2000, set the starting point for the creation of regional wholesale markets for electricity. Independent system operators (ISOs) and regional transmission organizations (RTOs) then formed market regions with day-ahead wholesale markets for electricity.

[10] https://www.epsa.org/industry/primer/?fa=wholesaleMarket

[11] We focus on markets for which hourly electricity prices are available. If a market uses half-hourly prices, we define the hourly price as the average of the two half-hourly prices.

Currently there are seven organized markets in the U.S. These are ISO New England, New York ISO, PJM, Midwest ISO, Southwest Power Pool, ERCOT, and California ISO. Whereas some of those markets focus (approximately) on a single state (e.g., ERCOT covers most of Texas), others serve regions with multiple states (e.g., PJM covers all or part of 13 different states).[12] According to EPSA, two-thirds of the United States' economic activity occurs within the boundaries of these markets. States outside these markets still do not have competitive markets for electricity, so in these states, electricity is still supplied by regulated utilities.

In Europe, the process of deregulating electricity markets and introducing wholesale markets for electricity was started in 1996 by the European Union Directive 96/92/EC. By the early 2000s, the majority of all E.U. markets were deregulated. European markets are generally organized as day-ahead markets, and most but not all wholesale markets in Europe cover one country. Nordpool, the largest electricity market in Europe, is an important exception and covers several northern European countries.

In Asia and Oceania, the deregulation process varied across countries. Australia was an early adopter and started introducing wholesale markets in the mid-1990s. It now has multiple markets, which generally cover single states. There are no markets for which we are able to get data during our sample period in South America and Africa.

Overall, we collect hourly electricity prices for 41 power markets located in 30 countries. We do not consider markets which were active for less than two years during our sample period, markets without day-ahead trading, and markets without hourly pricing.[13] Figure 1 illustrates the regions of the world that supply electricity competitively through wholesale markets. These regions cover a large portion of the developed economic world. However, while the basic structure of electricity markets is similar across the globe, the markets differ in a number of ways. For this reason, we focus on time-series variation in the

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[12] For simplicity, we assume that a market exists in a state if it covers all or most of the state according to the FERC.
[13] For this reason, we do not include the Southwest Power Pool (starting in 2013), IBEX in Bulgaria (2014), EPIAS in Turkey (2015), and CROPEX in Croatia (2016). Furthermore, we ignore markets which do not feature a typical day-ahead market with hourly pricing (WESM, Philippines). Hourly electricity prices could not be obtained for the markets in Brazil, Argentina, and Colombia.

volatility of electricity prices in our empirical tests because of potential cross-regional differences that are potentially difficult to control for econometrically.

2.2. Wholesale Price Risk and Production Flexibility

Price risk faced by electricity producers should vary as a function both of the market and also by production technology. In some markets, demand for electricity is relatively stable and easy to forecast, leading wholesale prices to be relatively stable. However, in other markets, demand can fluctuate substantially and be difficult to predict accurately. For example, a heat wave in Texas in early August 2011 led to an electricity supply shortage and boosted prices peaks of more than 2,000 USD per MWh (the average price being around 30 USD per MWh).[14] In contrast, the electricity price went down to around *negative* 150 USD per MWh in Germany in May 2016.[15] The reason for this negative price was a combination of higher than expected production by wind turbines and the inflexibility of other power plants, which continued producing despite the negative price. Fluctuating wholesale prices impose adjustment costs on electricity producers, since they cannot store electricity easily if prices are low, and must pay setup costs to increase production if prices are high. Furthermore, because there is no way to dispose of electricity costlessly, these firms have to sell all the electricity they produce, even if the price is negative. Thus, wholesale price volatility creates a demand for liquidity from electricity producing companies, since unforeseen price fluctuations impose incremental costs on these firms.

Electricity producing firms differ from one another in terms of their exposure to price risk, because they face differences in regional demand fluctuations and also because their methods of producing electricity have different costs of adjusting output. Since electricity producers sell their product in the wholesale market, their revenues will vary with the price they receive in the wholesale market. Because consumers' demand for electricity tends to be price inelastic, a shock to demand can lead to large changes in wholesale prices. Supply curves of electricity producing firms, in contrast, can be relatively elastic, so changes in prices can lead firms to desire to adjust quantities substantially. Therefore, the

[14] https://www.eia.gov/todayinenergy/detail.php?id=3010

[15] http://www.independent.co.uk/environment/renewable-energy-germany-negative-prices-electricity-wind-solar-a7024716.html

ability to adjust output quantities at relatively low cost in response to price movements can be very valuable to electricity producers.

The cost to electricity producers of changing output varies dramatically with the method they use to produce electricity. The average cost of adjusting output for each of the main technologies is summarized in Table 1. Gas-fired power plants are very flexible, with run-up times of only several minutes and a low cost for starting the plant.[16] Gas combined cycle power plants are also quite flexible, with run-up times of about 90 minutes. However, for other production technologies the time needed to stop and start the plants and the associated cost can be considerable. For example, lignite-fired plants need about six hours to start at a cost of about 35 Euro per megawatt of production capacity, while coal-fired power plants cost about 50 Euro per megawatt. The most inflexible technology is nuclear power, since it can take days to shut down or restart a plant, with a very high cost of doing so (above 100 Euro per megawatt).

The total cost associated with starting and stopping of plants to electricity producing firms can be sizable. To gauge the magnitude of these costs, consider an average sized firm with 15 coal-fired plants. The average capacity of a coal-fired plant is 750 megawatts and the cost of cycling a coal plant (stopping and restarting it), is about $56 per megawatt, so each cycle costs about $42,000 per plant. If there are 50 cycles per year at each plant, the total cost is about $31.5 m annually per firm, which is more than 10% of the annual net income for a typical firm in our sample.[17]

The importance of production flexibility for energy utilities is highlighted by the existence of negative electricity prices in many markets. In this context, the European Power Exchange states that "[n]egative prices are not a theoretical concept. Buyers are actually getting money and electricity from

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[16] For wind and solar power, start costs and time are zero as these technologies are typically not actively dispatched (we present a robustness test later which excludes these technologies to ensure that they do not bias our findings).

[17] These cost estimates are for "warm starts", which means that the plant is not totally shut down. Costs for "cold starts", in which the plant is completely shut down would be higher, but these events are much rarer. Estimates for the number of warm start-ups of coal-fired plants varies slightly between different sources, but 50 is an average estimate. For instance, the International Energy Agency estimates that a typical coal-fired plant has about 45 warm starts per year (see Trueby, 2014, p. 19), whereas data from Aptech suggests more than 50 start-ups for coal-fired plants (see Leyzerovich, 2007, p. 316).

sellers. However, you need to keep in mind that if a producer is willing to accept negative prices, this means it is less expensive for him to keep their power plants online than to shut them down and restart them later."[18] The fact that electricity prices are sometimes negative increases the value of being able to adjust output at low cost, as well as the downside risk that firms with inflexible production face from price volatility.

2.3. Empirical Implications

Uncertainty about future prices combined with high inflexibility creates price risk for electricity producers. If the wholesale price changes substantially, then the optimal response of the suppliers would be to move along the supply curve and adjust output accordingly. However, it takes time to change output, e.g., by shutting down a power plant, especially for firms producing electricity with inflexible technologies. For this reason, an inflexible producer will be left producing a suboptimal quantity after a demand shock for a period of time. Because it is costly to change output, inflexible suppliers sometimes choose to produce a suboptimal quantity for limited periods of time rather than pay the costs of stopping and restarting the plant. Regardless of whether a firm pays to shut down a plant temporarily or continues to operate at a loss, the firm can suffer a cash flow shock when there are declines in the wholesale price.

The potential of such cash flow shocks provides a reason why electricity producers should use liquidity management. Almeida, Campello, Cunha, and Weisbach (2014) formally model a problem similar to the one faced by electricity producers. In this model, the firm faces an uncertain cash flow requirement to continue a valuable investment so holds cash in anticipation of the potential cash flow shock. A clear implication of this model is that when the magnitude of a potential cash flow shock increases, a firm should hold more cash in anticipation of a cash flow shock. This effect is lessened when a firm has better access to capital markets or can hedge the cash flow shocks in other ways, such as through a derivatives market.

For electricity producers, the potential cash flow shock arises from the risk coming from uncertainty about the wholesale price of electricity when there is inflexibility in their production process.

[18] https://www.epexspot.com/en/company-info/basics_of_the_power_market/negative_prices

When price uncertainty is low and/or production flexibility is high, such price risk is relatively unimportant. However, when price uncertainty is high *and* the cost of adjusting production is high, price risk is substantial, increasing the probability of negative cash flow shocks. Consequently, firms are expected to hedge such price risk ex ante by holding more liquidity. In addition, we expect this hedging via liquidity effect to be larger when firms are more likely to be financially constrained and when they do not have access to derivative markets that can be used to hedge cash flow shocks directly.

3. Data Description

3.1. Sample of Electricity-Producing Utilities

To construct a sample of energy utilities from all over the world, we start by combining lists of active and inactive utility companies from *Thomson Reuters*. We focus on publicly-traded utilities because reliable data for unlisted firms is often not available. The sample covers the years 1999 to 2014, which is the period for which we can obtain the necessary data on firms' production assets.

We perform several steps to clean the sample. First, we eliminate all firms without a primary security classified as equity. Second, we wish to consider only companies that focus on the generation of electricity. To ensure that other companies are not included, we rely on firms' SIC and ICB codes, the business description obtained from *Capital IQ*, and additionally conduct manual research on the companies' business lines. This process leads to a sample of 481 utilities for which we are able to obtain data on production assets. For much of the analysis, we focus on the subsample of the 253 firms that are located in regions that have wholesale markets for electricity during some portion of our sample period. These firms are located in 33 different electricity markets and have a total of nearly 40,000 unique power plants.

Table 2 provides a detailed overview of the composition of the sample over time. The number of sample firms increases significantly over time. The main reason for this increase is that many regions deregulated their electricity markets and created wholesale markets during our sample period.

3.2. Wholesale Electricity Price Data

To measure the degree of electricity price volatility, we use hourly data on electricity prices in each market. These data are available for 41 regional markets from 30 countries. Most countries have their own national market but some markets cover more than one country (e.g., Nordpool, which covers several Northern European countries) and some countries have more than one market (i.e., Australia, Canada, and the U.S.). We obtain the price data from the websites of the power exchanges, direct contact with those exchanges, or from *Thomson Reuters*. To make the prices comparable across countries, all prices are converted into U.S. dollars.

Table 3 provides descriptive statistics for electricity prices in each market. It is evident from this table that there is substantial variation across the world in electricity prices. Prices are highest in markets in Japan and Singapore, which have to import resources to produce electricity. In each of these markets, the mean and median wholesale prices are around $100 per megawatt hour. In contrast, prices in the Russian wholesale market, which has abundant energy resources, average about one fifth of this level, $22 per megawatt hour.

To illustrate that there are consistent differences across markets, we present in Figure 2 a time series plot of electricity price times for one month (January 2012) in three selected markets: the German market, the Italian market, and Nordpool, which covers several Northern European countries. This figure indicates that the degree of fluctuations varies considerably between different markets and over time. Even though all three markets are for developed European countries, the Italian market consistently has higher price than the German market's price, which is in turn higher than the price in Nordpool.

Since our goal is to evaluate the way in which wholesale price fluctuations affect firms' liquidity management, we calculate a measure of the price fluctuations in a particular market. To do so, we first match all sample firms to electricity markets based on their geographical location. We calculate a measure we refer to as *VOLATILITY*, which equals the standard deviation of returns of hourly electricity prices during a firm's fiscal year. Daily prices, which are simply aggregations of hourly prices because the hourly contracts are those which are typically traded, are less precise than hourly prices for our purpose.[19] Returns are calculated as differences between hourly prices in U.S. dollar and standardized by the average price in a market. Table 2 presents statistics on *VOLATILITY* in each market. This measure of price volatility varies substantially across markets, with an average of .05 for Russia, .08 for Nordpool, and over 2 for the Australian markets.[20]

3.3. Measuring Production Flexibility

Our measures for production flexibility are based on the generation technologies of the sample firms' power plants. Data on the production technologies for single power plants is obtained from the annual versions of the *Platts World Electric Power Plant* database. This comprehensive database contains information on power plants and their technologies around the globe. It includes information on single power plant units, including their production technologies, capacities, geographic locations, start dates of commercial operation, and their owners/operators.[21]

We obtain this database for all years between 2000 and 2014 and manually match each power plant in this database to the energy utilities sample.[22] About 50% of the plants match to our sample firms; the remainder are owned by large utilities that are not publicly listed and are excluded from our sample for this reason. These data on production processes allow us to calculate the degree of production flexibility for each firm in each year.

[19] For example, assume a daily price of 100 USD. If the price was 100 USD for all hourly contracts, it would have been optimal to run coal-fired plants in all hours. However, if the price was zero for 12 hours and 200 for the other 12 hours, switching on and off the plant would have been the optimal strategy. These two cases cannot be distinguished when using daily prices. Nevertheless, we perform a robustness test with daily prices and find similar, but slightly weaker results (which is to be expected due to the loss of measurement precision).
[20] An alternative approach is to use longer time intervals to calculate volatility, since the decision to shut down plants is presumably made for longer than hourly periods. We construct measures for daily and annual volatility below in section 4.4.1 and the results using these measures are similar to those using hourly volatility.
[21] A detailed description of the database is provided by Platts' Data Base Description and Research Methodology (www.platts.com/IM.Platts.Content/downloads/udi/wepp/descmeth.pdf). Reinartz and Schmid (2016) contain additional information about it as well as other information about electricity markets.
[22] We use the yearly version of the database because they only include the current owner/operator. For 1999, we use the database version of 2000 but exclude all power plants that were started after 2000.

Based on these data, we follow Reinartz and Schmid (2016) and use *RUN-UP TIME* as a measure of production flexibility for a particular firm-year. *RUN-UP TIME* is calculated as the capacity-weighted average run-up time:

$$\text{RUN-UP TIME}_{i,t} = \frac{\sum_{k=1}^{M} \text{Capacity}_{k,t} \cdot \text{Run-up time}_k}{\sum_{k=1}^{M} \text{Capacity}_{k,t}}$$

with index i for firm, t for year, k for production technology and M for the number of different technologies. The technology specific values for run-up time and their sources are summarized in Table 1. We define *FLEXIBILITY* as one minus the normalized *RUN-UP TIME* (i.e., the run-up time divided by the maximum value of *RUN-UP TIME*). This measure for flexibility is bounded between zero and one, with higher values being associated with greater production flexibility.[23]

3.4. Financial variables

Our measure of cash holdings is calculated as total cash holdings of the firm divided by book value of assets. Control variables included in all models are size (measured as the natural logarithm of total assets), cash flow (earnings before interest, taxes, depreciation, and amortization scaled by total assets), and GDP (the natural logarithm of the GDP per capita).[24] In additional tests, we also control for several other possible determinants of cash holdings, such the market-to-book ratio (market capitalization divided by the book value of equity), capital expenditures (scaled by total assets), leverage (total debt divided by the sum of total debt and book value of equity), and dividend payments (a dummy variable which equals one if a divided is paid). Fiscal years that end between January and June are allocated to the previous year; only complete fiscal years are considered. To restrict the impact of outliers, all financial variables are winsorized at the 1% and 99% levels.

3.5. Descriptive statistics

[23] In robustness tests, we use alternative measures for production flexibility based on ramp-up cost, full-load hours, and a relative ranking of all production technologies.
[24] All financial variables are measured in U.S. dollars. Both the measure of cash holdings and the control variables have become standard in the literature on cash holdings since Opler, Pinkowitz, Stulz and Williamson (1999).

Table 4 shows the descriptive statistics for our sample firms, averaged for the whole sample period. On average, energy utilities have cash holdings equal to eight percent of their total assets. This is comparable to values reported for multi-industry samples (see Almeida, Campello, Cunha, and Weisbach (2014)). Furthermore, there is considerable variation in the cash ratio with an inter-quartile range of nine percentage points. The average firm in our sample has total assets of around 18 billion USD (median: 4 billion USD). The average electricity price is 56 USD per megawatt hour (MWh), with 25^{th} and 75^{th} percentiles of 33 and 68 USD per MWh, respectively. The average value of *VOLATILITY* is 0.36, with considerable variation as indicted by the standard deviation of 0.76. The average run-up time is 3.7 hours with a standard deviation of 5.1, while *FLEXIBILITY* has an average value of 0.91. Our sample firms contain an average of 235 different power plants and use 6 different production technologies.

4. Estimating the Impact of Price Risk on Utilities' Liquidity

4.1. Empirical Specification

To measure the impact of price risk on utilities' liquidity management decisions, we estimate the extent to which utilities' cash holdings reflect price risk coming from wholesale price uncertainty and the inflexibility of the production process. As emphasized by Duchin, Gilbert, Harford and Hrdlicka (2017), this variable includes holdings of a number of securities, some of which are risky. Firms do, of course, have other ways managing liquidity; for example, they can acquire lines of credit, build debt capacity, or hedge through derivatives markets. We focus on cash holdings for two main reasons. First, cash is straightforward to measure and has been the focus of the prior empirical literature. Second, there are theoretical reasons why cash is the preferred way of managing liquidity. Lines of credit and debt capacity can disappear during poor financial conditions when they are most needed, effectively being used to fund overinvestments in good times rather than efficient investments in poor times (see Acharya, Almeida and Campello (2007) or Almeida, Campello, Cunha, and Weisbach (2014)). Hedging price risk by pre-selling electricity in the OTC or futures markets is common in many markets; we address this possibility and analyze how it affects our findings below in Section 5.2.

We estimate equations predicting an energy utility's cash holdings. We use the measures of price volatility and production flexibility we discussed above as our primary independent variables. Because of cross-sectional differences caused by firm-level, country-level, and market-level factors, we include firm fixed effects in all equations. The inclusion of these firm fixed effects implies that the important variation in the data determining our estimates are time series changes undergone by individual firms rather than differences across firms. We include year fixed effects to control for factors that affect the entire industry at any point in time. Finally, we include the firm's log (assets), its cash flow (normalized by assets), and GDP per capital (in 2010 USD) in each equation.[25]

4.2. Estimates of the Way Wholesale Price Volatility and Production Flexibility Affect Cash Holdings

We present these estimates in Table 5. The results presented in Column (1) suggest that higher wholesale price volatility is associated with higher cash holdings, while higher production flexibility leads to lower cash holdings. This pattern is consistent with theoretical predictions because both higher price volatility and lower production flexibility are associated with higher price risk. When production is more flexible, the cost of adjusting output is lower, so utilities with more flexible production approaches hold less cash on their balance sheets.

Theoretically, according to a model such as Almeida, Campello, Cunha, and Weisbach (2014), what should affect liquidity choices is the expectation of cash requirements. This expectation equals the product of the likelihood of a required cash inflow with the quantity of the required cash inflow conditional on one being needed. The likelihood of a cash inflow requirement is a function of the uncertainty of wholesale prices, and the size of any potential cash flow shock is a function of the inflexibility of the production process used. Therefore, we expect that the magnitude of each of these variables will affect the impact the other has on liquidity. In other words, utilities that have a high price risk due to both inflexible production methods and high product price uncertainty should adjust their cash

[25] The reported t-statistics are based on cluster-robust Huber/White standard errors (White, 1980), clustered by countries.

holdings more in response to an increase in price volatility than utilities with more flexible production methods.

To evaluate this hypothesis, we split the sample in two subsamples based on the flexibility of the production process used. In Column (2) of Table 5, we reestimate our equation on the subsample of observations for which *FLEXIBILITY* is above the median value in a country and year, and in Column (3), we reestimate the equation on the subsample in which *FLEXIBILITY* is below the median in a country and year. The results suggest that impact of price volatility on cash holdings comes primarily from the sample of firms with relatively inflexible production technologies. The coefficient on volatility for the subsample of firms using flexible production technologies is very close to zero; for those firms using inflexible technologies, it is much larger and the difference between the two is statistically significant. The positive impact of volatility on cash holdings appears to be driven by firms with inflexible production technologies. In contrast to flexible firms, these energy utilities cannot easily adjust their production in case of adverse price shocks. Because of the possibility of an unexpected cash flow shock, these firms build up liquidity buffers if the electricity price is highly volatile.

This pattern suggests that the appropriate specification of our model includes a term interacting price volatility with our measure of production flexibility. In Column 4 of Table 5, we present estimates of the equations including this interaction term and in Column 5 we reestimate this specification with additional control variables. In each specification, the estimated coefficient on the interaction term is negative and statistically significantly different from zero.

The estimated magnitude of this effect is substantial. According to the estimates presented in Column 5, a one-standard deviation increase of the electricity price volatility would translate into an about five percentage-point increase (in absolute terms) of the cash to total assets ratio for the most inflexible firms. Since the average cash ratio in our sample is 0.08, this increase represents a more than 50 percent change in relative terms. For a firm with average flexibility, a one-standard deviation increase in volatility would go along with a 0.6 percentage-point increase of the cash ratio, nearly a ten percent relative change. These calculations emphasize the importance of production flexibility, since the impact of high wholesale price volatility on an electricity-producing firm's cash holdings is much more pronounced for firms using inflexible methods of producing electricity.

In addition to these statistical analyses, we also plot the relationship between electricity price volatility and cash holdings in Figure 3, separately for all firms, firms with high production flexibility, and those with low flexibility. Here, electricity price volatility is set to zero for firms in regions without wholesale markets for electricity. For all firms, we find a clear correlation between cash holdings and price volatility. When looking at the sub-samples of firms with high and low production flexibility, we find that this comovement is driven by firms with low production flexibility. Thus, this graphical analysis confirms the implications of the estimated regressions: inflexible firms react to an increase in price volatility with higher cash holdings.

4.3. Identifying the Equation Using Weather Uncertainty as an Instrument for Price Volatility

The estimates in Table 5 are all based on firm-fixed effects estimations and thus are based on variation of wholesale price volatility over time rather than across firms. While it is unlikely that one firm's financial policies can have a major impact on the volatility of wholesale price volatility, it is conceivable that electricity price volatility in a market could be correlated with other time-variant country factors, such as economic growth expectations. If these factors affect firms' production flexibility at the same time, they could lead to correlation between volatility and the residuals in the estimated equations.

To address such concerns and to identify the impact of price risk on firms' liquidity policies more cleanly, we exploit the fact that electricity prices are heavily influenced by an exogenous factor – the weather. One of the most important factors influencing electricity demand is the temperature. Energy utilities typically apply sophisticated temperature forecasting models and plan electricity supply accordingly.[26] Since adjustments in the electricity supply are costly and slow, electricity prices react with an increase in volatility if uncertainty about future temperatures is high and temperature forecasts change frequently. Thus, electricity price volatility should increase if temperatures are difficult to forecast.

[26] Because energy utilities use sophisticated weather forecasting techniques, measures based on deviations of actual temperature from historical averages are unlikely to have a strong effect on price volatility. Expected temperature changes also lead to price changes, but these changes are less pronounced compared to unexpected demand shocks.

Using this logic, we construct an instrument for electricity price volatility based on how unpredictable future temperatures are in a power market. We obtain data on historical weather forecasts from *Intellovations*, and consider all 3-day forecasts for various locations in the U.S., which are available between 2005 and 2014.[27] We do not obtain only an aggregated forecast, but also individual forecasts from six different forecast providers. Based on these data, we construct the variable *WEATHER FORECAST UNCERTAINTY*. We start by calculating the forecast error for each forecast provider for each location on each day, defined as the squared difference between the forecasted and actual average temperature at a specific location. To measure the uncertainty of forecasts, we then calculate the standard deviation of these temperature forecast errors across different forecast providers. Lastly, we calculate the average of this standard deviation for each market and year. High values of *WEATHER FORECAST UNCERTAINTY* imply that there is high uncertainty among forecast providers about the future weather, so that it is difficult to estimate future electricity demand precisely.

We present estimates of the equation using this instrument for firms with low flexibility in Panel A of Table 6, and those with high flexibility in Panel B of Table 6. First, we estimate a simple firm-fixed effects regression with the uninstrumented volatility variable in Column (1) as baseline model. As before, we find a positive effect of volatility on cash holdings for the subsample of firms with low production flexibility. As a next step, we replace volatility with *WEATHER FORECAST UNCERTAINTY* and find similar results in Column (2).

In the last two columns, we conduct an instrumental variables analysis. For *WEATHER FORECAST UNCERTAINTY* to be a valid instrument for electricity price volatility, it must be unrelated to the residuals in the equations predicting firms' cash holdings but correlated with electricity price volatility. The weather is clearly exogenous to any firm-level decisions.[28] To evaluate whether it is related to electricity price volatility, we estimate a first stage regression, in which we predict electricity price

[27] A comprehensive time series of weather forecasts is only available for the U.S; forecasts for most other countries start in 2012, and coverage is much weaker than for the U.S. Thus, we focus on the U.S. markets in this test, using more than 10 million daily temperature forecasts to construct the instrument.

[28] Except possibly those involving the firm's CO_2 emissions.

volatility as a function of *WEATHER FORECAST UNCERTAINTY*. Estimates of this equation, reported in Column 3, indicate that *WEATHER FORECAST UNCERTAINTY* clearly predicts movements in electricity price volatility (with K-P rk Wald F statistics of above 20). Therefore, because *WEATHER FORECAST UNCERTAINTY* is exogenous but correlated with electricity price volatility, it appears to be a valid instrument. In Column (4), we analyze the impact of volatility on cash holdings using the instrumented values for volatility. As in the specifications reported in Table 5, we find a strong and positive impact of variations in the electricity price and firm liquidity for firms with low flexibility that is virtually the same magnitude as in the fixed effect specification in Column 1. Overall, this finding suggests that the relation changes in electricity price volatility occurring because of weather uncertainty causally affect a firm's liquidity management decisions.

4.4. Robustness

We have argued that electricity-producing utilities face risk coming from uncertain wholesale prices they receive for their electricity and inflexible production. This price risk can lead to negative cash flow shocks, so firms hold more liquidity in response to this risk. We have provided evidence suggesting that firms do adjust their liquidity in this fashion. We now present a series of tests designed to ensure that these results are robust to alternative specifications, definitions of variables, and other choices we have made in designing our empirical tests.

4.4.1. Measurement of Volatility

The measure we use for the volatility of electricity prices is based on hourly electricity prices. An alternative approach would be to use daily or annual prices instead of hourly prices. Daily prices are the average of all 24 hourly prices within a day. Although they are less precise than hourly prices because they ignore hourly variation (which can be a very important factor for start/stop decisions of power plants), we use them as robustness test. Annual prices reflect long-term changes in the cost of electricity, but cannot be used to calculate the volatility within a firm's fiscal year because there is only one price observation per year. Thus, we estimate the volatility of electricity prices as the standard deviation of the returns from the previous four years. These data have the advantage of providing a more long-term perspective on price volatility, although they are measured at much longer intervals so cannot capture short term changes in price volatility.[29]

In Columns (1) and (2) of Table 7, Panel A, we present estimates of the main equation using measures of price volatility constructed using daily and four years prior annual data on electricity prices. Although the measurement of volatility is very different from that in the equations presented above, the results are similar. Higher volatility still leads to higher cash holdings and this effect is concentrated in firms using inflexible approaches to producing electricity. Our results do not appear to depend on any particular approach we use to measure electricity price volatility.

4.4.2. Measurement of Flexibility

Our main flexibility measure is based on the run-up time of a particular technology, which measures how long it takes to restart a power plant. In Columns (3) and (4) of Table 7, Panel A, we apply two alternative measures of production flexibility. The first is based on a relative ranking of the technologies flexibilities based on run-up time. Higher rank values are assigned to more flexible technologies so that a higher value of this measure indicates more production flexibility. These technology-specific values for ranking are summarized in Table 1.

The second alternative flexibility measure is based on ramp-up cost, which is an estimate of the cost for a hot start of a power plant (in Euro per megawatt). A higher ramp-up cost indicates less production flexibility. The estimates of ramp-up cost are also summarized in Table 1. Similar to our main flexibility measure which is based on run-up time, we first calculate the capacity weighted average ramp-up cost for a firm and year, normalize it by dividing it by its maximum value, and then calculate the flexibility proxy as one minus the normalized ramp-up cost.

The estimates of the equations using these alternative approaches to measuring production flexibility are similar to the ones presented above in Table 5. In each estimated equation, higher volatility leads to higher cash holdings and that this effect is concentrated in inflexible firms.

[29] The data on annual electricity prices is obtained from the Energy Information Administration (EIA) for U.S. states and from the International Energy Agency (IEA) for all other countries.

4.4.3. Sensitivity to Particular Technologies

One potential concern is that the differences we observe across technologies do not reflect the differences in flexibility, but instead occur because of one or two particular technologies that are different for some reason. For example, nuclear power is likely to contain risks not present with other technologies that could lead firms using nuclear power to have more liquid balance sheets, although it is not clear why those risks would lead to a relation between cash holdings and price volatility. Furthermore, the cost structures of nuclear power plants are opaque because cost for the final deposition of nuclear waste are often unclear and difficult to consider. Nonetheless, in Panel B of Table 7, we reestimate our equation excluding individual technologies to ensure that the results are general and are not driven by the idiosyncrasies associated with any particular technology. In Columns (1) to (4), we exclude all firm years that have at least one plant with the following technologies: nuclear, coal, and gas. Another possible concern is that certain types of power plants are not actively switched dispatched (i.e., switched on and off). In particular, wind and solar plants produce electricity whenever there is wind or sun with little active dispatching of such power plants. To a smaller extent, this concern also applies to hydro power plants. To analyze whether such not actively dispatched power plants bias our results, we exclude all firm-years of utilities operating any of these three technologies in Column (4). The results are similar to those in the main specification in Table 5. Thus, it does not appear that the use if any particular technology is driving our results. Regardless of which firms are included into the equation, their liquidity decisions appear to be a function of both the price volatility and the flexibility of the production technology.

4.4.4. Other Alternative Specifications

In Panel C of Table 7, we present several additional specifications to evaluate the robustness of our empirical results. First, we replace our main measure for liquidity (cash holdings scaled by total assets) with the natural logarithm of cash holdings scaled by total assets. The estimates using this alternative dependent variable are presented in Column (1) and are very similar to our main specification in Table 5.

In Columns (2) and (3), we only consider observations of firms that account for less than 10% or 5% of the market's total capacity. It is possible that if firms have a large market share, they can manipulate the wholesale prices and could potentially not be price takers in this market. In the subsample used to estimate this equation, the average firm accounts for only 2.5% (median: 1%) of the market's total capacity, so is unlikely to have power to influence prices. The estimates in this equation are nonetheless similar to those reported above. In Column (4) we exclude small energy utilities operating fewer than 25 power plants. None of these alternative specifications changes the results substantially.

5. Cross-Sectional Differences

5.1. Financial Constraints

As Keynes (1936) originally pointed out, liquidity management and financing constraints are fundamentally linked. If financial markets work as well as most models in the finance literature assume they do, firms' liquidity decisions would be irrelevant. However, if financial markets contain frictions making it costly for firms to issue debt or equity, liquidity management becomes important. In the case of electricity production, this logic implies that it should be more important for firms to hedge price risk through liquidity management when firms are more financially constrained.

We evaluate the extent to which the relation between firms' cash holdings and price risk varies with the financial constraints facing the firms in our sample. To do so, we construct four measures of financial constraints: firm size (with smaller firms being more constrained), a dummy variable indicating that the firm has issued a syndicated loan, a dummy variable indicating that the firm has a bond rating, and a dummy variable that indicating if the firm resides in a common law country (which is likely to be related to access to equity financing).[30] As before, we split the sample into high and low flexibility firms and interact our measure for volatility with a dummy variable which equals one for the subset of firms that are less likely to face financial constraints and zero otherwise.

[30] We find similar results using other measures of access to equity capital such as the anti self-dealing index.

The estimates are reported in Columns 1-8 of Table 8. They suggest that regardless of the measure we use to construct the subsamples, the impact of electricity price volatility on cash holdings in firms using inflexible methods of producing electricity is much more pronounced for the financially constrained subsamples (i.e., small firms, those without syndicated loan issuances, those without a bond rating, and those with worse access to equity financing). For firms using inflexible technologies, price volatility does not affect cash holdings regardless of whether the firms are likely to face financial constraints. This pattern suggests that the extent to which firms change their liquidity in response to wholesale price volatility varies dramatically with the costs firms face in accessing capital markets. The dependence of the observed relation between corporate liquidity and price volatility on access to financial markets provides support for the view that the relation that we have documented does reflect the precautionary motive for holding cash.

5.2. Hedging through Derivatives Markets

An alternative to holding cash as liquidity is to hedge directly using derivatives. Derivatives can substitute for cash holdings because they transfer cash flows to the states of the world where they are most valuable (Froot, Scharfstein and Stein, 1993). However, derivatives are imperfect substitutes because they only allow firms to hedge risks for which appropriate markets exist, and the use of these markets for hedging is limited by their liquidity.

In the case of electricity markets, the relevant markets are the futures or forwards markets, in which firms can sell part of their output in advance. Doing so at least partly protects them from fluctuations in the day-ahead spot market. However, hedging opportunities vary substantially across power markets: some markets have very liquid electricity forward and/or future trading, while it is difficult to hedge price risk in other markets. For instance, a report by the Economic Consulting Associates (2015) on European electricity forward markets and hedging products "found weaknesses in liquidity in many forward energy markets with only Austria, Germany and the Nordic area exhibiting high levels of churn" (p. VII).

To evaluate the importance of derivative markets on liquidity management decisions, we again divide the sample into firms with high and low flexibility and interact volatility and evaluate the extent to which the existence of a liquid derivatives market exists affects the relation between price volatility and cash holdings in each subsample. We manually classify each power market as having a liquid derivatives market or not based on multiple sources. First, we use the percentage of a country's annual electricity demand that is traded in hedging products (i.e., forward or futures) as proxy for the availability of hedging products. Data for this proxy is available for European countries from a report by the Economic Consulting Associates (2015). Furthermore, we are able to collect the necessary information for this dimension for the Australian markets from an OECD report ("Infrastructure to 2030") and for New Zealand from the market operator. Second, we use information from a survey among market participants that was conducted for the European Commission.[31] Data on this measure is only available for European countries. Lastly, we collect information on the availability of hedging products from industry reports, newspaper articles, or publications by the operators of the power markets or electricity exchanges.[32]

We present estimates of these equations in Columns (9) and (10) of Table 8. We find that volatility affects cash holdings in inflexible firms much more when firms have poor hedging opportunities. When liquid derivative markets exist, firms can more easily sell their electricity in advance and hedge the risk coming from price fluctuations. However, if derivative markets do not exist or if they are not sufficiently liquid, then firms change their cash holdings in response to volatility changes. This finding provides direct evidence that hedging through derivatives markets is a substitute for holding cash.

5.3. Payout Policy

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[31] In this survey, active market participants were asked to rate the ability to trade forwards as "weak," "moderate," or "strong" (see "Review and analysis of EU wholesale energy markets", 2nd July 2008).

[32] For instance, neither of the two previous measures is available for PJM, but there is strong evidence that the trading of forwards and futures is quite liquid for this market. Thus, we would set the general liquidity of PJM to high. Classifying markets this way, we define markets to have a liquid hedging derivative product are AMEO NSW, AMEO QLD, AMEO VIC, AESO, APX UK, CAISO, EPEX Switzerland, EPEX Germany, EPEX France, ERCOT, EXAA, IESO, ISO New England, MISO, Nordpool, NYISO, OTE, and PJM. Markets without liquid hedging products according to our classification are AMEO SA, AMEO WA, ATS, BELPEX, EMC, EMI, GME, HUPX, IEX, JEPX, KPX, NP LITHUANIA, OMIE PORTUGAL, OMIE SPAIN, OPCOM, and TGE.

The results to this point suggest that electricity-generating firms adjust their cash holdings as a function of price risk due to uncertainty in the power price and inflexible production. However, it is not clear from these results exactly how the utilities go about adjusting their output. One possibility is that the utilities make adjustments to their payouts as a way of managing their cash balances.

We evaluate the extent to which firm manage their liquidity through adjustments through payout policy. To do so, we estimate equations predicting utilities' payouts as a function of *VOLATILITY* and *FLEXIBILITY*, as well as the interaction of the two. We also include firm-level control variables that potentially also explain payouts, and firm and year fixed effects. The firm fixed effects imply that even though the dependent variable in the equations is the level of payouts, they measure the level relative to the firm's average payout over the sample period. Consequently, the equations measure the effect of the independent variables on the abnormal payout level for the firm in question.

We present estimates of this equation in Table 9. This table includes four columns, each of which contains estimates using a different dependent variable: the natural logarithm of total payouts (dividends plus share repurchases), total payouts normalized by the firm's market capitalization, the natural logarithm of dividends, and dividends normalized by the firm's market capitalization. In each column, the coefficients have the opposite sign from those predicting cash holdings in Table 5: higher price volatility decreases payouts, and the positive coefficient on the interaction term implies the negative effect of volatility in payouts comes primarily from firms using inflexible technologies. The fact that payouts decrease in exactly the same circumstances as when liquidity increases suggests that the two effects are related. These results are consistent with the view that the changes in utilities' liquidity due to changes in price risk come from adjustments to their payouts.

6. Deregulation as a Source of Risk

The results we have presented suggest that electricity producing firms' cash holdings change with the volatility in wholesale prices, especially when firms use a relatively inflexible technology to produce the electricity. The implication of this result is that volatility in wholesale prices leads to volatility in electricity-producing firms' cash flows that they compensate for by holding additional cash. Presumably, if the price electricity producing firms received were either constant or a function of the firms' costs, then they would choose to hold less cash, since holding cash is tax disadvantaged in most countries and creates potential agency problems. Under deregulation, electricity-producing firms sell in the wholesale market, and must bear price risk they do not have to bear in a regulated environment. This risk leads electricity producing firms to add liquidity to their balance sheets, the cost of which should be considered when making regulatory decisions.

An implication of this view is that producing firms that operate in deregulated markets should face more risk, and consequently hold more cash, than otherwise similar firms who operate in regulated markets. This prediction can be tested in our sample, since of the 452 electricity-producing firms for which all the necessary data is available, 213 change from regulated to deregulated markets during our sample period, and the remaining 253 are in regulated or deregulated markets for the entire sample period. Using the larger sample of both regulated and deregulated firms, we reestimate the equation presented throughout the paper. We include a dummy variable *Market* equal to 1 if the firm sells its electricity in a wholesale market in a particular year, and 0 otherwise. Estimates of this variable measure the incremental cash held by deregulated firms relative to otherwise similar regulated ones.[33]

We present estimates of this equation in Table 10. In Column 1, we present the basic specification without country and firm fixed effects and in Column 2, we include country fixed effects. In Column 1, the estimated coefficient on *Market* is .018, and in Column 2 it is .015, each of which is statistically significantly different from zero. Since the mean cash holdings (normalized by assets) is .08, this equation implies that deregulation leads to about a 20% increase in firms' cash holdings.

[33] Because most markets were deregulated in the late 1990s and early 2000s, we use 1995 as the starting year for this test. Furthermore, electricity wholesale markets typically require some time to become fully functional, we exclude the start year and the year thereafter. For this test, we use the start year of the wholesale market in each country. In most cases, this corresponds to the start year of the wholesale price data as summarized in Table 3. For some countries, the wholesale market started before the data on prices became available. Brazil, Chile, and Colombia started a market during our sample period, but electricity price data for these markets is not available.

In Column 3, we include firm fixed effects to control for factors that vary by firm or country. With firm fixed effects, *Market* is perfectly correlated with the fixed effects when firms are either deregulated or regulated throughout the entire sample period. Consequently, in this specification, *Market* is identified from the firms that switch from being regulated to deregulated in our sample period. In this fixed effect specification, the estimated coefficient on *Market* equals .02, slightly larger than the coefficient in the specification without firm fixed effects. This coefficient implies that having to sell electricity through a wholesale market leads firms to increase cash holdings by 25%. Finally, in Column 4, we include *Flexibility* and *Flexibility* interacted with *Market* into the equation.[34] The estimates in this equation also imply that having a market increases firms' cash, and presumably the risk they are exposed to. It also suggests that the impact of a market on firms' cash holdings is larger for firms with inflexible production technologies, for which it is more costly to adjust their output in response to price movements.

7. Conclusion

One of the most important decisions a financial manager must make concerns the liquidity of the firm's balance sheet. Holding cash is costly for tax and other reasons, while at the same time it can insulate the firm from the obligation to raise external capital should there be an unexpected cash shortfall. We evaluate firms' decisions to hold cash by isolating one specific source of risk faced by firms in one industry: the risk faced by electricity producing firms when electricity wholesale prices are volatile and their production is inflexible.

We estimate the extent to which firms' balance sheets vary with the potential price risk they are likely to face. Our analysis makes use of variation in hourly wholesale regional electricity price data to measure the likelihood that firms will desire to change the amount of electricity they produce, and of data on firms' power plants to measure the flexibility of the firms' production processes. We focus on firms' cash holdings, since cash holdings are the easiest way that firms can adjust the liquidity of their balance sheet.

[34] We use flexibility values as of 2000 for years prior to 2000.

Our estimates imply that firms' cash holdings are positively related to both demand fluctuations and the cost of adjusting production. Firms operating in markets with more volatile prices and firms with more inflexible production technologies for which altering output is costly, tend to hold more cash. In contrast, electricity price uncertainty has little impact on firms' cash holdings if their production flexibility is high. This pattern is consistent with the view that firms' liquidity choices reflect the expected costs of price risk.

To isolate the channel through which wholesale electricity price volatility affects producing firms' liquidity choices, we rely on the fact that movements in electricity prices often occur because of weather-induced demand shocks. We construct an instrument for electricity price volatility based on the uncertainty of future weather, and reestimate the equations predicting electricity producing firms' liquidity choices using instrumental variables. Instrumenting for volatility this way, we find the same pattern as when we use our baseline firm-fixed effects models for estimation: price volatility leads to changes in cash holdings, with this relation much stronger for firms using methods of production for which it is more difficult and costly to change output quantities. This result suggests that price risk causally affects firms' cash policy in the manner suggested by the precautionary theory of liquidity.

We evaluate several cross-sectional predictions of the precautionary theory of liquidity management. A key assumption underlying the precautionary theory is that it is costly to access financial markets. Therefore, we expect that the dependence of liquidity on changes in price volatility will be stronger for firms that have a higher cost of external finance and are likely to be financially constrained. Using four alternative measures of the cost of external finance, our results imply that regardless of the measure we use, firms' changes in liquidity in response to changes in price risk are substantially larger for firms more likely to be financially constrained.

In addition, the ability of firms to hedge price risk through futures or forward markets by selling a portion of their electricity in advance through the derivative market varies across countries. The ability to hedge in this manner is potentially a substitute for holding liquidity. Empirically, we find that, consistent with this argument, the existence of a more liquid futures or forward market in electricity reduces the impact of price risk on firms' liquidity choices.

To understand the manner in which firms change their liquidity in response to demand shocks, we estimate the way in which firms' payouts respond to changes in price risk. The results imply that the factors that lead firms to increase their liquidity are exactly the opposite of those that increase payouts; payouts increase with *reductions* in volatility with this effect larger for firms with inflexible production processes. This finding suggests that one way in which firms change their liquidity is through changes in their payouts.

Wholesale price volatility appears to increase the risk faced by electricity producers, who compensate by holding more cash on their balance sheets. This additional risk faced by electricity producers is a consequence of the deregulatory environment. As a test of this idea, we compare the cash holdings of firms operating in regulated markets to those operating in deregulated ones. Consistent with the notion that deregulation increases the risk faced by electricity producers, our results suggest that firms selling on wholesale markets hold about 20-25% more cash than otherwise identical firms in regulated markets.

Overall, our findings suggest that in the electricity producing industry, price risk can be an important factor affecting firms' liquidity choices. The flexibility of the production process is a major factor affecting this risk. The electricity producing industry provides a useful laboratory for studying liquidity management issues, since we can observe the production processes and output price volatility. However, it is likely that price risk affects liquidity management choices in a similar manner in other industries as well.

Our analysis highlights the fact that firms' balance sheets are endogenous, and that economy or industry level factors can affect them. In doing so, these factors can impose potentially substantial costs on firms that have not been fully appreciated. First, deregulating the electricity industry had the effect of forcing producers to face wholesale price risk, and compensate for this risk by holding more cash than they otherwise would. The cost firms face from having to adjust their balance sheets is real effect of deregulation that has not been fully appreciated. Second, the results emphasize an important implication of more liquid capital markets; in particular, more liquid capital markets mean firms can hold less liquid balance sheets. Since it is costly for firms to hold liquidity, when a country adopts policies that lower the cost of external finance, a consequence is that firms in that country can hold less cash. Third, more active derivative markets mean firms can hold less liquid balance sheets. Again, since it is costly for firms to hold liquidity, the effects of liquid derivative markets on firms' balance sheets is a social benefit of having such markets.

References

Acharya, Viral V., Heitor Almeida and Murillo Campello (2007) "Is Cash Negative Debt? A Hedging Perspective on Corporate Financial Policies," *Journal of Financial Intermediation*, 16, 515-554.

Almeida, Heitor, Murillo Campello, Igor Cunha, and Michael S. Weisbach (2014) "Corporate Liquidity Management: A Conceptual Framework and Survey," *Annual Review of Financial Economics*, 6, 135-162.

Almeida, Heitor, Murillo Campello, and Michael S. Weisbach (2004) "The Cash Flow Sensitivity of Cash," *Journal of Finance*, 59, 1777-1804.

Bates, Thomas W., Kathleen M. Kahle, and René M. Stulz (2009) "Why do U.S. firms hold so much more cash than they used to?" *Journal of Finance* 64, 1985–2021.

Becher, D. A., J. H. Mulherin, and R. A. Walkling (2012) "Sources of gains in corporate mergers: Refined tests from a neglected industry," *Journal of Financial and Quantitative Analysis* 47:57–89.

Boldt, Jenny; Hankel, Lisa; Laurisch, Lilian Charlotte; Lutterbeck, Felix; Oei, Pao-Yu; Sander, Aram; Schroeder, Andreas; Schweter, Helena; Sommer, Philipp; Sulerz, Jasmin (2012) "Renewables in the grid. Modeling the German power market of the year 2030," *Working Paper*.

Campello, Murillo, Erasmo Giambona, John R. Graham, and Campbell R. Harvey (2011) "Liquidity management and corporate investment during a financial crisis," *Review of Financial Studies* 24, 1944–1979.

Duchin, Ran, Thomas Gilbert, Jarrad Harford and Christopher Hrdlicka (2017) "Precautionary Savings with Risky Assets: When Cash is not Cash," *The Journal of Finance*, forthcoming.

Economic Consulting Associates (2015) "European Electricity Forward Markets and Hedging Products – State of Play and Elements for Monitoring," *Final Report*.

Epstein, Larry (1978) "Production Flexibility and the Behaviour of the Competitive Firm under Price Uncertainty," *Review of Economic Studies*, 45, 251-261.

Erel, Isil, Yeejin Jang, Bernadette A. Minton, and Michael S. Weisbach (2017), "Corporate Liquidity, Acquisitions, and Macroeconomic Conditions," *Working Paper.*

Fabrizio, K., N. Rose, and C. Wolfram. 2007. "Do markets reduce costs? Assessing the impact of regulatory restructuring on US electric generation efficiency," *American Economic Review* 97, 1250–77.

Federal Energy Regulatory Commission (2015) "Energy Primer: A Handbook of Energy Market Basics."

Froot, K.A., D.S. Scharfstein, and J.C. Stein (1993) "Risk Management: Coordinating Investment and Financing Policies," *The Journal of Finance*, 48, 1629-1658.

Hoberg, Gerard, Gordon Phillips, and Nagpurnanand Prabhala (2014) "Product market threats, payouts, and financial flexibility," *The Journal of Finance*, 69, 293–324.

Keynes, John Maynard (1936), “The General Theory of Employment, Interest and Money,” (McMillan, London).

Leyzerovich, Alexander S. (2007) “Steam Turbines for Modern Fossil-Fuel Power Plants”, CRC Press Inc., Tylor & Francis Group.

Liang, Jiaqi and Ronald G. Harley (2010) “Pumped storage hydro-plant models for system transient and long-term dynamic studies,” *Power and Energy Society General Meeting, 2010 IEEE.*

Lins, Karl V., Henri Servaes, and Peter Tufano (2010) “What drives corporate liquidity? An international survey of cash holdings and lines of credit,” *Journal of Financial Economics* 98, 160–176.

Moody’s Investor Service (2016) “Australian utilities' operational flexibility is key to their ability to manage power price volatility,” report summary available at https://www.moodys.com/research/Moodys-Australian-utilities-operational-flexibility-is-key-to-their-ability--PR_354068

Morellec, Erwan, Boris Nikolov, and Francesca Zucchi (2014) “Competition, cash holdings, and financing decisions,” *Working Paper*, Swiss Finance Institute.

Opler, Tim, Lee Pinkowitz, Rene M. Stulz, and Rohan Williamson (1999), “The Determinants and Implications of Corporate Cash Holdings,” *Journal of Financial Economics*, 52, 3-46.

Peltzmann, Sam and Winston, Clifford (2000) “Deregulation of network industries - What’s next?” Washington, DC: AEIBrookings Joint Center for Regulatory Studies.

Pérez González, Francisco and Yun, Hayong (2013) “Risk Management and Firm Value: Evidence from Weather Derivatives”, *Journal of Finance*, 68, 2143-2176.

Reinartz, Sebastian and Thomas Schmid (2016) “Production Flexibility, Product Markets, and Capital Structure Decisions,” *Review of Financial Studies*, 29, 1501-1548.

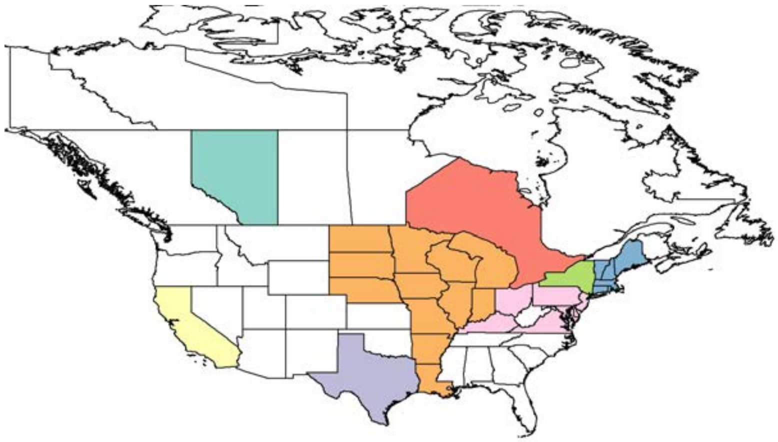
Rettl, Daniel A., Alex Stomper, and Josef Zechner (2016) “The Stability of Dividends and Wages: Effects of Competitor Inflexibility,” *Working Paper*.

Sandmo, Agnar (1971) “On the Theory of the Competitive Firm Under Price Uncertainty,” *American Economic Review*, 61, 65-73.

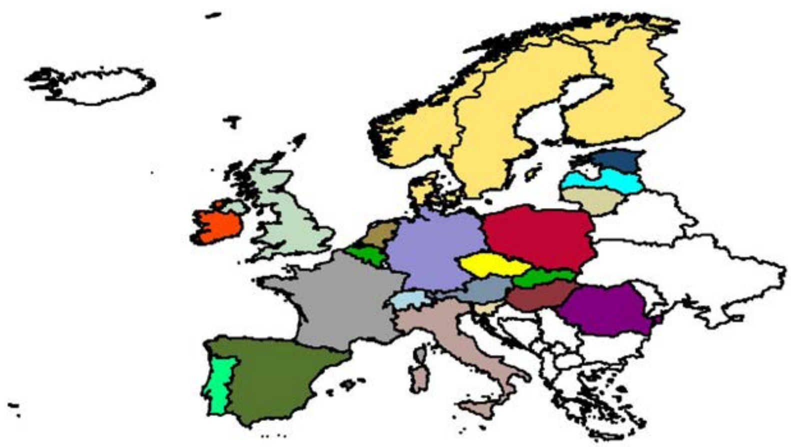
Swider, Derk Jan (2006) “Handel an Regelenergie- und Spotmärkten”, (Springer, Wiesbaden)

Trueby, Johannes (2014) “Thermal Power Plants Economics and Variable Renewables Energies”, *International Energy Agency Insight Series*.

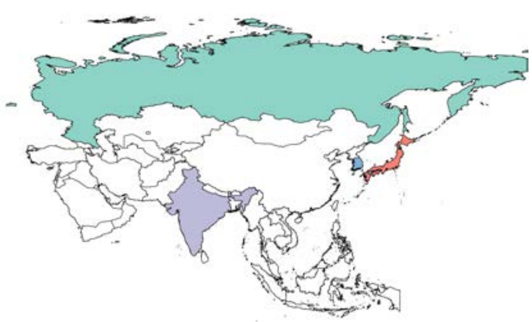
Turnovsky, Stephen J. (1973) “Production Flexibility, Price Uncertainty and the Behavior of the Competitive Firm,” International Economic Review, 14, 395-413.



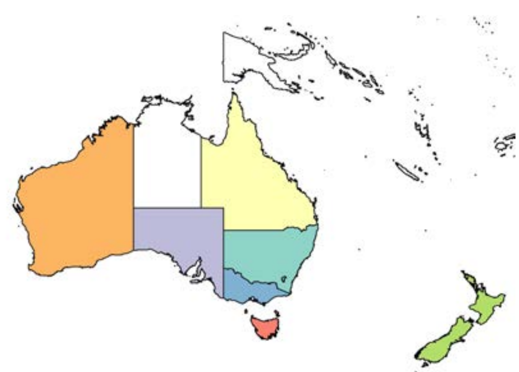
(a) North America



(b) Europe

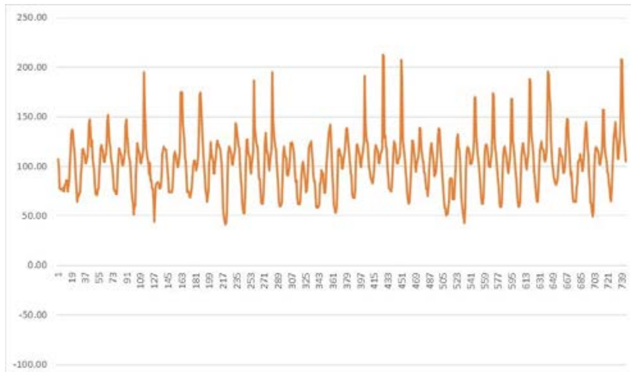


(c) Asia

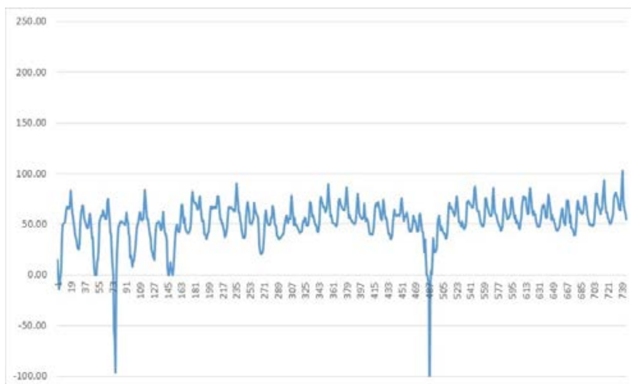


(d) Oceania

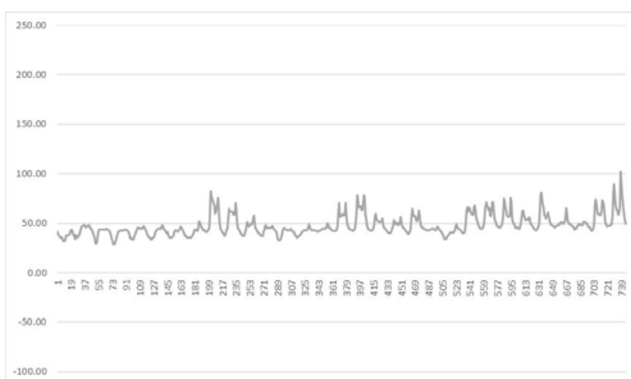
Figure 1: This figure shows the different regions which have competitive wholesale markets for electricity and are included in our sample.



(a) GME (Italy)

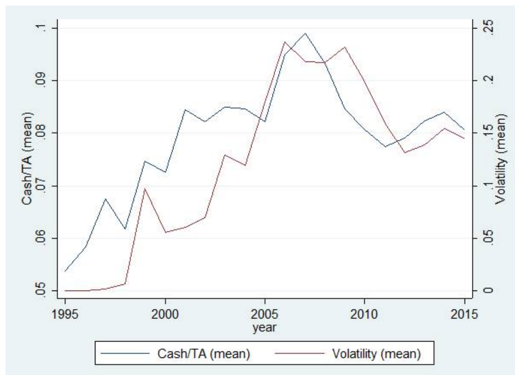


(b) EPEX_D (Germany)

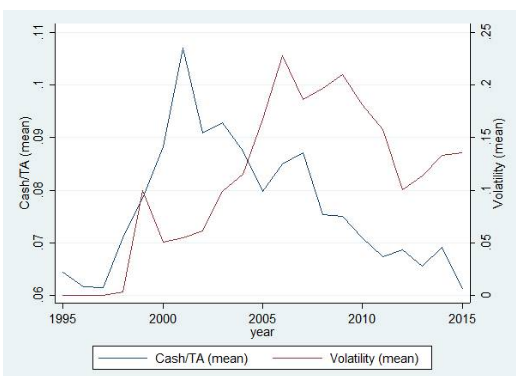


(c) Nordpool (Northern Europe)

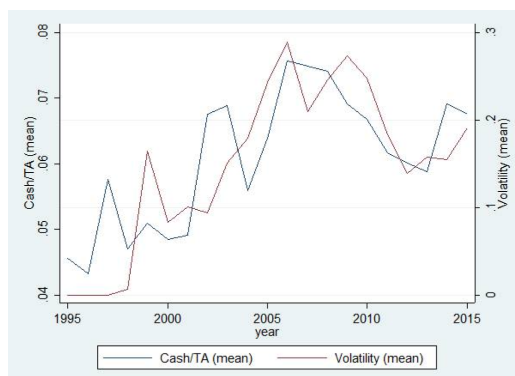
Figure 2: This figure shows hourly electricity prices (in USD per MWh) for three selected market in January 2012. The same price scales are used for all three markets. An overview on the included markets can be found in Table 3.



(a) all firms



(b) high production flexibility



(c) low production flexibility

Figure 3: This figure shows the development of cash holdings and electricity price volatility over time for all firms (a), highly flexible firms (b), and firms with low production flexibility (c). Electricity price volatility is set to zero for regions without a wholesale market for electricity. Only firms with more than ten observations are considered.

Table 1: Production technologies

Technology	**run-up time** hours	**ramp-up cost** USD per MW	**ranking** rank
Biogas	0.25	38.99	7
Biomass	2.00	56.82	5
Coal	3.00	56.82	4
Hydro	0.08	0.00	9
Gas	0.25	30.79	7
Gas comb. cycle	1.50	38.99	6
Geothermal	0.00	0.00	9
Lignite	6.00	43.26	3
Nuclear	40.00	160.83	1
Oil	0.08	30.79	8
Pump storage	0.02	0.00	9
Solar	0.00	0.00	9
Waste	12.00	56.82	2
Wind	0.00	0.00	9

Run-up time is measured in hours and refers to warm-starts in the case of thermal power plants. The values for coal, gas-combined cycle, lignite, and nuclear are based on Eurelectric's "Flexible Generation: Backing-up Renewables", p. 19. Danish Energy Agency's "Technology Data for Energy Plants" is the source for the values of biogas, biomass, and waste. Information from life-cycle power solutions provider Wärtsilä is used to calculate the run-up time for oil. The values for hydro and pump storage power plants are based on data from Duke Energy, FirstGen, MWH Global, and Liang and Harley (2010). The run-up time for solar and wind is zero, as such plants are usually not actively dispatched and start generation as soon as sun or wind are available. Similarly, zero run-up time is assumed for geothermal power plants.

Ramp-up costs are measured in USD per MW. The values for coal, lignite, nuclear, gas combined cycle, and oil are based on Boldt et al. (2012). Euro values are converted to USD based on the EUR/USD exchange rate at the end of 2014. We assume that ramp-up costs for gas power plants equal those of oil power plants and that ramp-up costs for geothermal, hydro, pump storage, solar, and wind power plants are zero. For biomass and waste power plants, we assume equal ramp-up costs as for coal plants. For biogas, we assume same cost as for gas combined-cycle.

Ranking is the relative ranking of all production technologies. The least flexible technology has a rank of one. The ranking is based on run-up time and ramp-up cost.

Table 2: Descriptive statistics: Sample

	Total		Wholesale Markets		
Year	**#Firms**	**#Plant Units**	**#Markets**	**#Firms**	**#Plant Units**
1999	209	15,020	7	37	2,710
2000	212	14,946	11	41	2,981
2001	211	17,383	12	49	4,677
2002	232	20,326	15	56	7,629
2003	255	22,142	19	73	9,520
2004	278	23,368	19	78	10,044
2005	313	25,857	21	103	14,239
2006	331	26,590	23	132	16,342
2007	355	28,020	26	146	17,232
2008	368	29,899	28	151	18,473
2009	374	30,818	29	195	20,657
2010	362	33,032	31	195	22,606
2011	357	34,025	33	196	23,336
2012	345	34,533	33	189	23,718
2013	340	35,563	33	187	24,202
2014	331	35,037	33	179	23,834
Total	4873	426,559	373	2,007	242,200
Unique	481	60,004	33	253	39,982

This table presents an overview on the sample firms and their power plant units for each sample year. Total refers to all firms, independent of their location. Wholesale markets refers to firms which are located in regions with competitive wholesale markets for which hourly electricity price data is available (cf. Table 3 for an overview on the different markets).

Table 3: Descriptive statistics: Electricity markets

Country	**Market**	**start**	**N**	**mean**	**median**	**vola**
Australia	AEMO_NSW	1999	158,395	32.14	33.03	3.11
Australia	AEMO_QLD	1999	158,395	33.70	27.36	2.95
Australia	AEMO_SA	1999	158,395	39.55	37.06	2.95
Australia	AEMO_TAS	2006	101,939	42.17	38.85	2.05
Australia	AEMO_VIC	1999	158,395	29.44	27.63	2.78
Australia	AEMO_WA	2007	90,000	43.58	46.15	0.26
Austria	EXAA	2003	129,552	51.59	54.04	0.21
Belgium	BELPEX	2007	87,672	61.47	60.55	0.43
Canada	AESO	2000	148,615	54.36	49.47	1.13
Canada	IESO	2003	128,616	32.96	33.29	0.56
Czech Republic	OTE	2010	60,617	49.51	48.85	0.16
Denmark	Nordpool	1999	157,800	39.94	38.45	0.09
Estonia	NP_EE	2011	61,368	49.96	50.48	0.28
Finland	Nordpool	1999	157,800	39.94	38.45	0.09
France	EPEX_F	2002	140,256	52.50	57.64	0.44
Germany	EPEX_D	2001	149,040	46.94	50.21	0.36
Hungary	HUPX	2011	56,539	57.36	56.43	0.31
India	IEX	2009	74,568	72.16	66.31	0.17
Italy	GME	2005	111,780	83.86	85.11	0.21
Japan	JEPX	2006	102,912	111.00	90.66	0.13
Korea	KPX	2002	137,376	85.54	88.34	0.12
Latvia	NP_LV	2014	35,064	55.63	46.50	0.25
Lithuania	NP_LT	2013	43,848	55.21	57.76	0.20
Netherlands	APX_NL	2000	157,800	54.22	54.44	0.48
New Zealand	EMI	1999	176,835	110.32	51.47	0.25
Norway	Nordpool	1999	157,800	39.94	38.45	0.09
Poland	TGE	2001	144,672	44.23	41.65	0.12
Portugal	OMIE_PT	2008	83,319	61.71	56.00	0.11
Romania	OPCOM	2006	100,765	53.89	48.49	0.18
Russia	ATS	2009	72,216	22.16	22.75	0.05
Singapore	EMC	2003	122,736	99.91	93.72	0.43
Slovakia	OKTE	2010	61,361	50.02	49.46	0.19
Spain	OMIE_SP	1999	166,527	49.30	51.35	0.13
Sweden	Nordpool	1999	157,800	39.94	38.45	0.09
Switzerland	EPEX_CH	2007	96,432	69.53	66.34	0.25
United Kingdom	APX_UK	2004	121,080	66.43	65.98	0.23
United States	CAISO	2010	61,361	34.84	32.32	0.13
United States	ERCOT	2011	52,602	31.74	27.41	1.15
United States	ISONE	2003	121,320	54.06	53.72	0.13
United States	MISO	2006	95,856	33.93	30.81	0.19
United States	NYISO	2000	148,903	49.46	46.15	0.14
United States	PJM	1999	164,376	39.91	37.14	0.26
Total/Average		2004	4,872,703	53.00	49.73	0.57

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Table 3 continued

This table presents summary statistics for the hourly electricity prices in the different markets. Prices are in megawatt per USD. Local prices are converted to USD using daily exchange rates. Reported are the first year for which data is available, number of observations (N), mean price, median price, and volatility. The start year for the data collection is 1999; the last year for which data is available is 2014 for all markets.

Table 4: Descriptive statistics: Firms

Variable	**Obs**	**Mean**	**p25**	**p50**	**p75**	**SD**
Cash	2,005	0.08	0.01	0.04	0.10	0.11
Assets (mio USD)	2,007	17,938	828	4,215	18,809	37,726
Assets (log)	2,007	15.07	13.63	15.25	16.75	2.08
Cash flow	1,979	0.08	0.06	0.09	0.11	0.07
MtB	1,799	1.64	0.90	1.35	1.89	1.44
Capex	1,955	0.08	0.04	0.06	0.09	0.10
Leverage	2,006	0.48	0.37	0.52	0.64	0.21
Dividend	1,977	0.76	1.00	1.00	1.00	0.43
GDP (USD per capita)	2,007	39,206	34,877	43,434	48,775	16,283
GDP (ln)	2,007	10.36	10.46	10.68	10.79	0.88
Electricity price	2,007	56.42	32.79	48.97	67.97	38.76
Volatility	2,007	0.36	0.11	0.17	0.29	0.76
$\text{Volatility}_{\text{daily}}$	2008	0.29	0.11	0.17	0.29	0.44
$\text{Volatility}_{\text{annual}}$	1253	0.08	0.03	0.07	0.12	0.06
Run-up time	2,007	3.71	0.25	2.25	4.21	5.10
Flex	2,007	0.91	0.89	0.94	0.99	0.13
Weather Forecast Unc.	453	10.71	9.79	10.49	11.49	1.53
#Plant Units	2,007	235	29	93	245	458
#Technologies	2,007	6.29	3.00	6.00	10.00	3.85

This table presents descriptive statistics for all sample firms located in regions with competitive wholesale markets for which hourly electricity price data is available. Reported are the number of observations (N), mean value, 25% percentile, median, 75% percentile, and standard deviation (SD). A detailed description of all variables can be found in Appendix A.

Table 5: Predicting Cash Holdings as a Function of Price Risk

Column	1	2	3	4	5
Sample	all	high flex	low flex	all	all
Volatility	**0.0058*** **	**0.00023**	**0.011*** **	0.071***	0.059***
	(3.65)	**(0.11)**	**(4.30)**	(4.65)	(3.48)
Flexibility	**-0.065***			-0.075**	-0.11**
	(-1.86)			(-2.46)	(-2.44)
Vol x Flex				**-0.068*** **	**-0.056*** **
				(-4.26)	**(-3.14)**
Log(assets)	-0.031***	-0.047***	-0.0043	-0.032***	-0.030**
	(-4.08)	(-5.47)	(-0.69)	(-4.11)	(-2.29)
Cash flow	0.036	-0.067	0.12*	0.036	0.058
	(0.81)	(-1.09)	(1.97)	(0.82)	(1.24)
Log(GDP per capita)	0.026	0.037	-0.033	0.025	0.011
	(0.37)	(0.44)	(-0.42)	(0.36)	(0.15)
Market-to-book					0.0011
					(0.27)
Capex					0.0026
					(0.12)
Leverage					0.0015
					(0.055)
Dividend					0.0018
					(0.20)
Firm-FE	yes	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes	yes
Observations	1,944	865	870	1,944	1,687
Firms	252	168	136	252	235
R2	0.74	0.74	0.74	0.74	0.76

The dependent variable is cash holdings [wc02001] normalized by total assets [wc02999]. Volatility is defined as the standard deviation of hourly electricity price changes, normalized by a market's average electricity price level. Flexibility is defined as the one minus the standardized run-up time of a firm's power plants. The sample is restricted to firms with a production flexibility which is higher (lower) than the median value in a particular year and country in Column 2 (Column 3). The sub-samples do not sum up to the full sample because the median firm in a market and year is not included. All models are firm fixed effects regressions. Control variables are lagged by one year. T-statistics based on Huber/White robust standard errors clustered by countries are presented in parentheses. ***, ** and * indicate significance on the 1%-, 5%- and 10%-levels, respectively. A detailed description of all variables can be found in Appendix A.

Table 6: Instrumenting Wholesale Price Volatility using Weather Forecast Uncertainty

Panel A: U.S. firms with low flexibility				
Column	1	2	3	4
Model	firm-FE		IV first	IV second
Volatility	**0.036****			
	(3.62)			
Weather Forecast Uncertainty		**0.0030****	**0.083*****	
		(2.97)	**(4.62)**	
$\text{Volatility}_{\text{instr}}$				**0.037****
				(2.31)
Log(assets)	0.0043	0.0049	0.017	0.0043
	(0.20)	(0.23)	(1.40)	(0.23)
Cash flow	0.047**	0.044*	-0.087	0.048***
	(2.82)	(2.47)	(-1.64)	(3.20)
Firm-FE	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes
Observations	222	222	221	221
K-P rk Wald F	n/a	n/a	21.4	

Panel B: U.S. firms with high flexibility				
Column	1	2	3	4
Model	firm-FE		IV first	IV second
Volatility	**-0.0066**			
	(-0.20)			
Weather Forecast Uncertainty		**-0.00017**	**0.067*****	
		(-0.053)	**(4.65)**	
$\text{Volatility}_{\text{instr}}$				**-0.0026**
				(-0.060)
Log(assets)	-0.061	-0.061	0.048**	-0.061
	(-1.31)	(-1.35)	(2.32)	(-1.47)
Cash flow	-0.64	-0.64	-0.0076	-0.64
	(-1.44)	(-1.44)	(-0.13)	(-1.62)
Firm-FE	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes
Observations	222	222	217	217
K-P rk Wald F	n/a	n/a	21.6	

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Table 6 continued

The dependent variable is cash holdings [wc02001] normalized by total assets [wc02999]. The sample for this test is restricted to U.S. firms with a production flexibility above the median in Panel A and those with a flexibility below the median in Panel B. Weather forecast uncertainty is the average standard deviation of the 3-day weather forecast error across different forecast providers in an electricity market and year. Weather forecast error is defined as the squared difference between the forecasted and actual average temperature at a specific location. IV stands for instrumental variables regression. T-statistics based on Huber/White robust standard errors clustered by countries are presented in parentheses. ***, ** and * indicate significance on the 1%-, 5%- and 10%-levels, respectively. A detailed description of all variables can be found in Appendix A.

Table 7: Robustness of Cash Predictive Models to Alternative Specifications

Panel A: Measurement of volatility and production flexibility				
Column	1	2	3	4
	volatility measures		flexibility measures	
	daily prices	annual prices	ranking	ramp-up cost
Volatility	0.051**	0.45**	0.028***	0.040***
	(2.39)	(2.42)	(5.02)	(3.42)
Flexibility	-0.065*	-0.096*	-0.0041	-0.029
	(-1.98)	(-1.90)	(-1.17)	(-0.81)
Vol x Flex	**-0.050****	**-0.53****	**-0.0036*****	**-0.043*****
	(-2.21)	**(-2.32)**	**(-3.75)**	**(-2.85)**
Log(assets)	-0.031***	-0.026**	-0.031***	-0.031***
	(-4.12)	(-2.62)	(-3.95)	(-3.92)
Cash flow	0.037	0.058	0.035	0.034
	(0.85)	(0.62)	(0.81)	(0.79)
Log(GDP per capita)	0.027	0.16***	0.024	0.025
	(0.38)	(3.92)	(0.35)	(0.36)
Firm-FE	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes
Observations	1,944	1,145	1,944	1,944
Firms	252	168	252	252
R2	0.77	0.83	0.74	0.74

Panel B: Exclusion of firms with a particular technology				
Column	1	2	3	4
Exclude	Nuclear	Coal	Gas	Hydro/Wind/Solar
Volatility	0.084***	0.099***	0.093**	0.074**
	(3.58)	(4.60)	(2.58)	(2.27)
Flexibility	-0.14	-0.072	-0.69**	-0.11*
	(-1.40)	(-1.51)	(-2.39)	(-1.86)
Vol x Flex	**-0.084*****	**-0.10*****	**-0.10****	**-0.077****
	(-3.34)	**(-4.43)**	**(-2.27)**	**(-2.37)**
Log(assets)	-0.034***	-0.036***	-0.033***	-0.019**
	(-4.13)	(-3.82)	(-3.12)	(-2.43)
Cash flow	0.047	0.057	0.17***	0.052
	(0.90)	(0.98)	(3.52)	(0.76)
Log(GDP per capita)	0.064	0.18	0.10	0.029
	(0.79)	(1.25)	(1.02)	(0.27)
Firm-FE	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes
Observations	1,494	796	604	416
Firms	218	130	100	93
R2	0.74	0.75	0.79	0.64

continued on next page

Table 7 continued

Panel C: Various alternative specification				
Column	1	2	3	4
	ln(cash)	<10% capa	<5% capa	$\geq$ 25 plants
Volatility	**0.68****	**0.073*****	**0.069*****	**0.063****
	(2.58)	**(4.42)**	**(4.80)**	**(2.62)**
Flexibility	-1.42***	-0.081***	-0.076***	-0.074
	(-4.21)	(-3.60)	(-3.17)	(-1.37)
Vol x Flex	**-0.59****	**-0.072*****	**-0.071*****	**-0.056****
	(-2.19)	**(-4.11)**	**(-4.53)**	**(-2.29)**
Log(assets)	-0.18	-0.036***	-0.039***	-0.031**
	(-1.50)	(-4.31)	(-4.53)	(-2.53)
Cash flow	0.63	0.044	0.063	-0.12**
	(1.21)	(0.91)	(1.15)	(-2.71)
Log(GDP per capita)	-0.12	0.10	0.12	-0.17***
	(-0.14)	(0.94)	(1.00)	(-3.10)
Firm-FE	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes
Observations	1,936	1,598	1,436	800
Firms	251	233	217	100
R2	0.69	0.75	0.75	0.71

The base specification is as follows: the dependent variable is cash holdings [wc02001] normalized by total assets [wc02999]; volatility is defined as the standard deviation of hourly electricity price changes, normalized by a market's average electricity price level; flexibility is defined as the one minus the standardized run-up time of a firm's power plants.

In *Panel A*, volatility is calculated as the standard deviation of returns of daily prices in Column 1 and annual prices (over the last four) in Column 2. Annual electricity prices in USD are based on EIA and IEA data. The alternative flexibility measures are ranking and ramp-up cost.

In *Panel B*, firm-years with plants using the technology specified in each column are excluded. Control variables are lagged by one year.

In *Panel C*, the dependent variable is the natural logarithm of cash holdings scaled by total assets in column 1. Only firms which account for less than 10% or 5%of the total production capacity in a country/state and year are considered in Column 2 and 3. In Column 4, only firms with more than 25 different power plants are considered. In Column 4, we exclude firms which operate in more than one electricity market.

All models are firm fixed effects regressions. Control variables are lagged by one year. T-statistics based on Huber/White robust standard errors clustered by countries are presented in parentheses. ***, ** and * indicate significance on the 1%-, 5%- and 10%-levels, respectively. A detailed description of all variables can be found in Appendix A.

Table 8: Cross-Sectional Differences in the Relation between Cash and Price Risk

Column	1	2	3	4	5	6	7	8	9	10
	Firm Size		**Syndicated Loans**		**Bond Ratings**		**Access to Equity**		**Hedging Opportunities**	
	low flex	high flex	low flex	high flex	low flex	high flex	low flex	high flex	low flex	high flex
Volatility	0.016***	0.00062	0.073**	-0.010	0.016***	-0.00022	0.029**	-0.0026	0.094**	-0.086
	(3.80)	(0.15)	(2.42)	(-0.60)	(3.91)	(-0.056)	(2.79)	(-0.25)	(2.36)	(-0.90)
$\text{Dummy}_{\text{unconstr.}}$	-0.0079	0.0038	...	...	0.0019	-0.052**	...	...		
	(-1.42)	(0.33)	...	...	(0.16)	(-2.34)	...	...		
Vol x $\mathbf{D_{unconstr.}}$	**-0.0088****	**-0.00076**	**-0.064***	**0.011**	**-0.0095****	**0.0015**	**-0.019***	**0.0031**		
	(-2.28)	**(-0.14)**	**(-2.08)**	**(0.66)**	**(-2.64)**	**(0.30)**	**(-2.00)**	**(0.32)**		
$\text{Dummy}_{\text{high}}$									...	...
									...	...
Vol x $\mathbf{D_{high}}$									**-0.083****	**0.087**
									(-2.10)	**(0.91)**
Log(assets)	-0.0030	-0.048***	-0.0033	-0.047***	-0.0040	-0.047***	-0.0045	-0.047***	-0.0032	-0.048***
	(-0.49)	(-5.58)	(-0.55)	(-5.49)	(-0.61)	(-5.95)	(-0.74)	(-5.46)	(-0.54)	(-5.67)
Cash flow	0.12*	-0.066	0.12*	-0.065	0.12*	-0.072	0.12*	-0.067	0.12*	-0.066
	(1.98)	(-1.09)	(2.00)	(-1.06)	(1.96)	(-1.15)	(1.98)	(-1.09)	(1.99)	(-1.05)
Log(GDP per capita)	-0.036	0.038	-0.037	0.035	-0.033	0.028	-0.031	0.037	-0.023	0.024
	(-0.46)	(0.45)	(-0.51)	(0.41)	(-0.42)	(0.33)	(-0.39)	(0.43)	(-0.38)	(0.24)
Firm-FE	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Observations	870	865	870	865	870	865	870	865	870	865
Firms	136	168	136	168	136	168	136	168	136	168
R2	0.76	0.72	0.76	0.72	0.76	0.72	0.76	0.72	0.76	0.72

The base specification is as follows: the dependent variable is cash holdings [wc02001] normalized by total assets [wc02999]; volatility is defined as the standard deviation of hourly electricity price changes, normalized by a market's average electricity price level; flexibility is defined as the one minus the standardized run-up time of a firm's power plants.

In Columns 1 to 6, we use firm size, syndicated loans, and bond ratings to split firms in financially constrained and unconstrained firms. For firms size, a firm is financially unconstrained if total assets are higher than the median total assets in a country and year. For syndicated loans, financially unconstrained are those firms which have issued a syndicated loan during our sample period. We define a firm to be financially unconstrained if S&P issued a long-term bond rating in the current or any previous year. In Columns 7 and 8, access to equity is high for countries with common law. Hedging opportunities in Columns 9 and 10 is set to one if the liquidity of the market for electricity price hedging products is high and zero if the liquidity is low or no such market exists. We classify each market based on multiples sources, such as newspaper articles, industry reports, or reports issued by the exchanges. Furthermore, we use date on the annual volume of electricity futures/forwards relative to demand from the "European Electricity Forward Markets and Hedging Products - State of Play and Elements for Monitoring" report by the Economic Consulting Associates and a survey for the European Commission which investigates the ability to trade forwards.

All models are firm fixed effects regressions. Control variables are lagged by one year. T-statistics based on Huber/White robust standard errors clustered by countries are presented in parentheses. ***, ** and * indicate significance on the 1%-, 5%- and 10%-levels, respectively. A detailed description of all variables can be found in Appendix A.

Table 9: Payout Policy as a way of Adjusting Cash Holdings for Price Risk

Column	1	2	3	4
	Payout	Payout/MC	Dividend	Div/MC
Volatility	**-2.36*** **	**-0.027** **	**-1.84** **	**-0.019***
	(-2.80)	**(-2.14)**	**(-2.57)**	**(-1.95)**
Flexibility	0.29	-0.0035	0.036	-0.0014
	(0.31)	(-0.13)	(0.029)	(-0.056)
Vol x Flex	**2.67*** **	**0.031** **	**2.21*** **	**0.021***
	(3.33)	**(2.26)**	**(3.30)**	**(1.97)**
Log(assets)	0.79***	0.0032	0.76**	0.0027
	(2.85)	(0.87)	(2.74)	(0.82)
Cash flow	6.21**	0.043***	5.63***	0.030***
	(2.53)	(3.63)	(3.40)	(3.20)
Log(GDP per capita)	-1.65	-0.037	-0.67	-0.031
	(-0.56)	(-0.69)	(-0.28)	(-0.79)
Firm-FE	yes	yes	yes	yes
Year-FE	yes	yes	yes	yes
Observations	1,605	1,480	1,923	1,748
Firms	236	225	252	239
R2	0.76	0.23	0.76	0.32

The dependent variable is the natural logarithm of 1 plus the total payout amount (i.e., dividends [wc04751] plus share repurchases [wc05376]) in Column 1 and total payout amount scaled by market capitalization [wc08001] in Column 2. Only dividends are considered in Columns 3 and 4. Volatility is defined as the standard deviation of hourly electricity price changes, normalized by a market's average electricity price level. Flexibility is defined as the inverse capacity-weighted average run-up time of a firm's power plants. Control variables are lagged by one year. Models are firm fixed effects regressions. T-statistics based on Huber/White robust standard errors clustered by countries are presented in parentheses. ***, ** and * indicate significance on the 1%-, 5%- and 10%-levels, respectively. A detailed description of all variables can be found in Appendix A.

Table 10: Measuring the Impact of Wholesale Markets on Cash Holdings

Column	1	2	3	4
Market	**0.018****	**0.015****	**0.020****	0.055***
	(2.12)	**(2.27)**	**(2.11)**	(2.85)
Flexibility$_{\mathbf{backfilled}}$				-0.012
				(-0.44)
Market x Flex$_{\mathbf{backfilled}}$				**-0.039***
				(-1.90)
Log(assets)	-0.015***	-0.013***	-0.025***	-0.024***
	(-6.76)	(-5.85)	(-5.39)	(-5.33)
Cash flow	0.064	0.055	0.14***	0.14***
	(0.83)	(0.70)	(3.49)	(3.48)
Log(GDP per capita)	-0.0014	-0.050**	-0.018	-0.018
	(-0.25)	(-2.56)	(-0.95)	(-0.95)
Country-FE	no	yes	n/a	n/a
Firm-FE	no	no	yes	yes
Year-FE	yes	yes	yes	yes
Observations	5,040	5,040	5,040	5,040
Firms	452	452	452	452
R2	0.099	0.25	0.25	0.25

The dependent variable is cash holdings [wc02001] normalized by total assets [wc02999]. Market is a dummy variable which equals on if a wholesale market for electricity exists in a region and year. The year in which a market is introduced and the first year thereafter are excluded because markets are frequently not fully functional at the beginning. Flexibility is defined as the one minus the standardized run-up time of a firm's power plants. For years before 1999, we use the earliest available flexibility value as approximation. Models are pooled OLS or firm fixed effects regressions. Control variables are lagged by one year. T-statistics based on Huber/White robust standard errors clustered by countries are presented in parentheses. ***, ** and * indicate significance on the 1%-, 5%- and 10%-levels, respectively. A detailed description of all variables can be found in Appendix A.

Appendix

Appendix A: Definition of variables

Variable	Description
Main Variables	
Cash	Cash & short term investments [wc02001] / total assets [wc02999].
Volatility	Standard deviation of returns of hourly electricity prices during the firm's fiscal year. Returns are calculated as differences between hourly prices in U.S. dollar and standardized by the average price in a market. Source: Own calculations based on hourly electricity prices.
Flexibility	One minus the normalized flexibility measure (default is run-up time). Normalizing means that the flexibility measures is divided by its maximum so that it is bound between zero and one. Source: Own calculations based.
Run-up time	Capacity-weighted average time which is necessary to start-up a power plant in hours. Based on the production technologies of the firms' power plants. Source: Own calculations based on WEPP database.
Weather Forecast Uncertainty	Weather forecast uncertainty is the average standard deviation of the 3-day weather forecast error across different forecast providers in an electricity market and year. Weather forecast error is defined as the squared difference between the forecasted and actual average temperature at a specific location. Source: Own calculations based on data on historic weather forecasts from Intellovations.
Other Variables	
Electricity Price	Average hourly electricity spot price in USD/MWh over the firm's fiscal year. Source: Own calculations based on hourly electricity prices.
Volatility (daily)	Equals the main volatility measure, but daily prices instead of hourly prices are used. Daily prices are caluclated as the average across all 24 hourly prices. Source: Own calculations based on hourly electricity prices.
Volatility (annual)	Standard deviation returns of annual electricity prices. We use windows of four years to calculate the standard deviation. Data is obtained from the EIA for U.S. states and the IEA for other countries. Source: Own calculations based IEA/EIA data.
Ranking	Relative ranking of the flexibility based on run-up time. Higher rank value are assigned to more flexible technologies. Source: Own calculations based on WEPP database.
Ramp-up cost	Capacity-weighted average cost for a hot start of power plant in €/MW. Based on the production technologies of the firms' power plants. Source: Own calculations based on WEPP database.
Control Variables	
Log(assets)	Logarithm of total assets [wc02999] in U.S. dollar.
Cash flow	Earnings before interest, taxes, depreciation, and amortization (EBITDA) [wc18198] / total assets [wc02999].
Log(GDP per capita)	Natural logarithm of GDP per capita (in 2010 U.S. dollar) in a country and year. Source: Worldbank.

Definition of Variables - continued

Variable	Description
Market-to-book	Market capitalization [wc08001] divided by book value of common equity [wc03501].
Leverage	Total debt [wc03255] / (Total debt [wc03255] + book value of common equity [wc03501]).
Capex	Capital expenditures [wc04601] scaled by total assets [wc02999] at the beginning of the respective year.
Dividend	Dummy variable which equals one if the firm pays a dividend [wc05376].