**A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Master of Science**

# Investment come rain or shine: Renewable energy exposure to weather risk, use of weather derivatives, and potential impacts



**Aaron Themus PERRY**

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# MESPOM

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**Author's declaration**

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Aaron T. PERRY

**CENTRAL EUROPEAN UNIVERSITY**

**ABSTRACT OF THESIS** submitted by:
Aaron Themus PERRY
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Weather derivatives are a relatively new financial product that have been used by energy companies to manage the volume risk associated with energy demand. It has been demonstrated that the use of these products can impact company value. The output of renewable energy plants, and therefore income from those plants, is related to the weather. Renewable companies are potential users of these weather derivative products. This thesis examines the extent to which weather variability affects renewables and the wider power market, how the use of weather derivatives could impact investment in renewables, and the current state and future of the weather derivatives market for renewables. A trio of research methodologies are used, including statistical analysis, interviews, and a review of annual reports. Weather derivative use can impact the investment in renewable energy, and there are several cases where they were explicitly used in financing, however, because they are not used regularly it was difficult to measure this effect on a wider scale. 'Alternative energy' companies were not found to have a significant linear correlation with wind speed, cloud cover, or precipitation, however lack of data and other factors affected the significance of these results. The weather derivatives market is growing slowly, with most of this growth coming from the over the counter trading. Products that could be used by renewable energy companies are in the minority, and the number of those products actually used by renewables is even smaller, but there are several isolated examples of their use.



**Keywords:** investment, renewable energy, weather derivative, risk, hedging, policy

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## List of Abbreviations

BADC – British Atmospheric Data Center

CDD – Cooling Degree Day

CME – Chicago Mercantile Exchange[1]

CPC – Climate Prediction Center

ECMWF – European Center for Medium-range Weather Forecasting

EIU – Economist Intelligence Unit

ENSO – El Niño Southern Oscillation

GDP – Gross Domestic Product

HDD – Heating Degree Day

IPCC – Intergovernmental Panel on Climate Change

LFG – Landfill Gas

NetCDF – Network Common Data Form

NCAR – National Center for Atmospheric Research

NCL – NCAR Command Language

OTC – Over the Counter

WRMA – Weather Risk Management Association



[1] The Chicago Mercantile Exchange is a wholly owned subsidiary of CME Group, a company that formed from the merger of the Chicago Mercantile Exchange and the Chicago Board of Trade. The terms are used interchangeably in this thesis.

# 1. Introduction

During early 1997 instruments monitoring sea surface temperatures off the coast of South America detected much warmer than usual water, one of the first signs of an El Niño year. The 1997 event would turn out to be one of the strongest on record (Burt 2014). El Niño itself is generally not considered a severe weather event, but part of a natural periodic cycle in the Pacific Ocean called the El Niño-Southern Oscillation (ENSO). However, the warm and cold phases of this cycle, known as El Niño and La Niña, can cause changes in weather patterns around the world (CPC 2012). While strong ENSO events can affect the probability of extreme weather events such as floods and hurricanes, no one event can be directly attributed to ENSO. Usually strong ENSO events are correlated with areas around the world being hotter or colder and/or wetter or dryer than usual (CPC 2012). These shifts whether they are large or small, have the potential to affect the economy in noticeable ways. A rainier than normal summer could mean lower ice cream sales and higher umbrella sales. A warmer winter could mean low jacket sales or fewer visitors to ski resorts, but a smoother season for transport companies. The UK Met Office estimated in 2001 that approximate 70% of firms in the United Kingdom were affected by the weather (UK Met Office 2001). An Allianz Risk Transfer (2013) report states that over 30% of the US Gross Domestic Product is directly or indirectly affected by weather, and normal weather variance could be as much as 3.4% of GDP. The energy sector is particularly vulnerable to this variation, with certain renewable energy technologies being particularly susceptible (Alexandridis and Zapranis 2013).

Warmer temperatures in the United States during the 1998/1999 La Niña event, combined with the publicity that the 1997/1998 El Niño received and the recent deregulation, and subsequent increased exposure to weather risk, of the energy sector, created the perfect conditions for a new risk management tool, the weather derivative, to be created (Randalls 2006;

Thornes 2003). This product allowed for the hedging of a previously unmanageable risk, and improved the value of conventional energy companies (Thornes 2003; Pérez-Gonzáles and Yun 2013). Similar weather derivative contracts may have the potential to give similar benefits to renewable energy companies as well.

## 1.1 Problem Statement

Since their inception in 1997 weather derivatives have helped traditional energy companies manage their weather-related risk, but very little is known about their use and effectiveness in relation to renewable energy. Numerous papers and studies have been published that look at the use and effectiveness of weather derivatives in their historical role in managing demand-side volume risk. Many authors state their belief that weather derivative have a place beyond this role in the traditional energy sector (Carr 2013; Fadhl *et al.* 2008; Moody 2006; Müller and Grandi 2000; Randalls 2006; Štulec *et al.* 2012; Štulec *et al.* 2013). A few examine their potential in other fields such as retail (Štulec *et al.* 2013). Some even explicitly mention renewable energy as an avenue for growth for the weather derivative market (Fadhl *et al.* 2008; Randalls 2006; Štulec *et al.* 2012; Carr 2013; The Economist 2012).

The weather derivatives market is opaque, with most trades being conducted over the counter, and only a few dozen derivative products traded on exchange. This makes data extremely scarce. The weather derivatives market is relatively young and growth has been slow. While much research has been done on the topic of pricing these contracts in general, there is little academic research on the use of weather derivatives in the renewable energy sector. Nor has much research been done on the wider effect this new type of risk management may have on growth and investment in that industry. The goal of this thesis is to contribute new research that will help to fill this void in public knowledge.

## 1.2 Research Aim, Objective, and Questions

### 1.2.1 Aim

The aim of this thesis is to determine how and to what extent weather derivative products are being used by publicly listed renewable energy companies to manage the supply-side volume risk associated with renewable power productions, as well as perspectives towards the use of these products and their impact on their attitudes towards renewable energy.

### 1.2.2 Objectives

The objectives of this thesis are twofold. First, is to gain a better understanding of the weather derivatives market, and how the weather can impact the renewable energy industry. Second is to examine how weather derivatives could affect investment in renewable energy.

### 1.2.3 Questions

This thesis will strive to answer three questions:

- To what is extent does weather variability affect renewable energy companies, and the power market?
- Could weather derivatives reduce the weather-related risks associated with renewable energy and encourage new investment?
- Are these products being used, or are there plans to use them in the future? Why or why not?



## 1.3 Chapter Overview

This thesis is broken in six additional chapters. Chapter 2 provides basic background information on weather derivatives, weather risk, and renewable energy. Chapter 3 goes through the literature available on renewable energy investment, risk management, and the weather derivatives market. Chapter 4 outlines the methodology used for both the quantitative and qualitative analysis. Chapter 5 gives the results and an analysis of the data collected. Chapter 6 provides a discussion of the methodology, results, and analysis, as well as a critical reflection of the results and potential avenues for future research. Chapter 6 wraps up the paper with a summary and conclusion.

# 2. Background

## 2.1 Weather derivatives

A weather derivative is a financial contract between two parties that offers payment when certain meteorological conditions occur. They are designed to hedge against mild changes in weather conditions such as the ENSO events described above. These contracts were developed by three large energy companies, Enron, Aquila, and Koch Industries in the United States in the late 1990s. The first trade was conducted by the Enron Corporation in 1997 (Thornes 2003; Pollard *et al.* 2008). The weather derivative market quickly expanded thanks to existing trading expertise at these companies, and the significant losses suffered by energy companies due to the mild 1998/1999 La Niña winter (Thornes 2003; Randalls 2006).

Energy production companies are particularly sensitive to changes in weather (Štulec *et al.* 2012). Consumer demand for energy is highly correlated with temperature during the summer and winter (Alaton *et al.* 2010). Prior to the deregulation of the energy sector in the US in the mid-1990s, companies would have been able raise rates or make an adjustment to bills to offset any losses that occurred during a mild winter. Deregulation made this type of compensation difficult if not impossible and the profits of these companies began to fluctuate with demand (Moody 2006). The first contracts were designed to mitigate the effects of temperature fluctuations on gas sales by offsetting losses in income due to adverse weather (The Economist 2012).

A generic weather derivative contract has seven parameters to it (Zeng 2000). (1) A contract has a defined period to it, this is typically a month or season. (2) The contract will definite which meteorological station will be the official reporting station, whose observations will be used to design and settle the contract. This station must be well established [same location for 10+ years] so the climatology of the station can be calculated for the determination of the strike [see below]. The station should also be in a secure location to prevent tampering, typically airport meteorological stations are used (Randalls 2006). (3) The contract will also define the weather index on which the derivative will be based. For temperature this is typically Heating Degree Days [HDD], which is a measure of cold days, or Cooling Degree Days [CDD], which is a measure of warm days. Wind futures may use the cumulative wind speed index or the Nordex wind speed index (Alexandridis and Zapranis 2013). Other indexes cover events such as rainfall, snowfall, frost, and hurricanes (CME Group 2014b). A selection of these indexes and their definitions is provided in Table 1. (4) The types of derivative contracts that can be traded include, but are not limited to, calls, puts, swaps, and collars. The definition of these options are provided in Table 2.

**Table 1. Examples of weather indexes**

| Index | Definition | Description | Source |
|---|---|---|---|
| **Heating Degree Day** | $HDD = \sum_{i=1}^{N} \max(0, 18°C - T_i)$ | A summation of the number of degrees below some reference level ($T_i$), summed over a number of days. Used in winter to measure the need for heating. The base indoor temperature is usually set around 18°C or 65° F.[2] | Zeng 2000 |
| **Cooling Degree Day** | $CDD = \sum_{i=1}^{N} \max(0, T_i - 18°C)$ | A summation of the number of degrees above some reference level (Ti), summed over a number of days. Used in winter to measure the need for cooling. The base indoor temperature is usually set around 18°C or 65° F. | Zeng 2000 |
| **Nordic Wind Speed Index** | $I(\tau_1, \tau_2) = 100 + \sum_{s=\tau_1}^{\tau_2} (W(s) - \omega_{20}(s))$ | Measure of daily wind speed deviations from 20 year mean over a period ($\tau_1$, $\tau_2$). Used by the US Futures Exchange to settle wind contracts when they traded weather derivatives. | Alexandridis and Zapranis 2013 |
| **CME Hurricane Index** | Proprietary, calculates potential damage from a hurricane based on maximum wind velocity and size. | Used construct binary [lump sum payout on trigger] weather derivative options that are traded on the CME exchange. | CME Group 2009 |



[2] This temperature is considered to be a comfortable temperature where no heating or cooling is required. Above this value and some people will use energy to cool their homes, below this value they'll use energy to heat it. This is a subjective value, and while 18°C or 65° F is the standard, it does vary somewhat by region. It can also be set to any arbitrary value, in which case the index is known as a Variable Degree Day (VDD). (Belakovskaia 2014)

The remaining contract options define how money will be exchanged. (5) The premium or price of the derivative should be set by the market, and can be estimated using numerous pricing methods. (6) The strike is threshold of the weather index that will trigger payout. (7) The tick is the amount of payout per unit of the weather index. Typically there is a cap to the amount that can be paid out on each contract. Alternatively, there may be a lump-sum payout when the strike is met, or, if a swap contract is used, some other non-monetary exchange may occur between the parties. The terms of a HDD weather derivative option traded on the Chicago Mercantile Exchange/CME Group are provided in Table 3.

**Table 2. Definition of derivative contract options. Source Investopedia 2014a, Investopedia 2014b, Investopedia 2014c, and Thornes 2003**

<table>
<tr><th>Contract</th><th colspan="2">Definition</th></tr>
<tr><td rowspan="2">Put option</td><td>Traditional</td><td>Gives buyer the right to sell a commodity as a specific price and time. Benefits when price drops.</td></tr>
<tr><td>Weather</td><td>"…compensate[s] buyer if a weather variable falls below a given threshold."</td></tr>
<tr><td rowspan="2">Call option</td><td>Traditional</td><td>Gives buyer the right to buy a commodity at a specific price and time. Benefits when price of commodity goes up.</td></tr>
<tr><td>Weather</td><td>"…compensate[s] buyer if a weather variables rises above a predetermined level."</td></tr>
<tr><td>Swap</td><td colspan="2">A contract in which two organizations agree to exchange risk. Useful when organizations have complimentary risks.</td></tr>
<tr><td>Collar</td><td colspan="2">A combination of buying a put option and selling a call option. This means that payments will occur outside of certain range of value, protects against extremes</td></tr>
</table>

In theory, these contracts can be traded between any two parties. However, in practice regulation dictates that only parties with a certain level of financial sophistication[3] can trade

[3] The Vortex Insurance Agency (2014), in their page comparing weather insurance to weather derivatives state that organizations who trade in weather derivatives typically need to meet certain financial 'eligibility standards', usually >$10 million in assets or $1 million in net worth.

derivatives (Vortex Insurance Agency 2009). Derivatives may be traded over the counter (OTC), privately between two parties, or through an exchange such as the Chicago Mercantile Exchange. An exchange facilitates the transaction process by standardizing the contracts, publishing market information, and bringing parties together to trade(Centola 2014). Those who trade on an exchange usually have no idea who the counter party is. Much less is known about OTC trades, since only the two parties involved in the trade know the terms of the contract, and very few have a good idea of the overall size of this side of the market.

**Table 3. CME HDD Option and Future Terms Source: CME Group 2014a**

| | |
|---|---|
| **Options information** | |
| Underlying Contract | One CME Degree Days Index (HDD) Futures Contract |
| Pricing Unit | Dollars per index point |
| Tick Size (minimum fluctuation) | Full Tick = 1 Index Point (= $20 per contract) |
| Contract Months* | Nov, Dec, Jan, Feb, Mar plus Oct and Apr |
| Strike Price Intervals | 1 index point in a range of 1 to 3200 index points |
| **Underlying Futures Contract** | |
| Contract Size | $20 times the respective CME Degree Days (HDD) Index |
| Product Description | Heating Degree Days (HDD) for US Cities |
| Pricing Unit | Dollars per index point |
| Tick Size (minimum fluctuation) | 1 index point (= $20 per contract) |

## 2.2 Weather risk

Energy companies, along with most other industries, are exposed to two types of risk, high-risk low-probability events, and low-risk high-probability events (Thornes 2003; Randalls 2006; Pollard *et al.* 2008; Moody 2006). High-risk low-probability events are severe weather events like hurricanes, flash floods, tornadoes, and hail. Low-risk high-probability events are weather conditions that only deviate slightly from climatological averages, or ‘normal’ conditions like a warmer or colder winter, or dryer or wetter spring. Thornes (2003) describes these events as 'regional climate anomalies'. The tools used to manage these risks, insurance and weather derivatives, are very similar. In fact, in some cases these deals can seem almost identical, with a contract only falling into one category or another after is has been (Randalls 2006). However there are a couple notable differences between them.

Risk transfer has historically been confined to the realm of insurance. However, in order for a company to be insured against a particular type of risk, several conditions must first be met (Randalls 2006; Pollard *et al.* 2008; Alaton *et al.* 2010; Moody 2006). The historical probability of the event in question occurring must either be known or able to be estimated. This is a necessity in the construction of both insurance and weather derivative contracts. Insurance requires an 'insurable' asset something that stands to be lost when the event occurs. In order for payout to occur the damage to the insurable asset must be directly attributable to the event that was insured against (Pollard *et al.* 2008). Premiums for insurance are determined by the value of the assets, and the risk of damage. This works well severe events with physical damage. The event, such as tornado, is clearly defined, and the value of the damage due to that event to a building or other asset is easily calculated. Damages from low-risk, high-probability climate anomalies are both difficult to determine and hard to attribute. There are also index-based insurance products in which payout is triggered by a meteorological event, but the amount of the contract is usually still tied to an asset, like the crop insurance designed by the World Bank in Malawi (2012).

It is easy to see now why a gap in risk management options existed when energy companies deregulated. The damage to businesses from regional climate anomalies is hard to determine. Although the vulnerability of businesses to small changes in weather can be calculated, determining causation for a change in revenue for any particular season is very difficult. Weather derivatives fill that gap by offering a method of risk management tied solely to meteorological phenomenon and not the assets of the contract holder. Any individual or organization that meets the financial requirements can enter into a contract, regardless of their exposure to risk. Companies who can determine the level of risk they are exposed to can purchase an appropriate amount cover in the form of derivative contracts. In theory, they could even buy contracts with a payout larger than their exposure using derivatives.

The weather derivatives market is not without some risks. Speculation is common in the exchange weather derivatives market (Randalls 2006). There is so much speculation, that those buying and selling weather derivatives for hedging purposes may be in the minority on exchanges, although this is not uncommon in other markets (Randalls 2006)[4]. While this speculation can add much needed liquidity to fledgling markets, several of Randalls' (2006) interviewees said it eroded the general perception of the market. As mentioned previously ideally the price of the derivative would be set by the market , but when trades are conducted OTC, extremely complex pricing models may be required (Alaton *et al.* 2010; Benth 2010).

## 2.3 Renewable Energy

Given weather derivative's beginning in the traditional energy industry it makes sense to also look at renewable producers as a potential user of these products, as they are exposed to many of the same risks. Both types of operators are subjected to the weather risks in the form of variable demand for energy. However; many types of renewable energy, including wind, solar, and hydro, are also susceptible to variability in supply. Out of the renewable energy plants with supplies that are vulnerable to changes in weather, wind appears to be particularly sensitive. Its relationship with the weather is consequently more complicated than the others. There is a wind speed below which a wind turbine will not generate power. Once above is, the amount of power produced is well correlated with wind speed. Unlike other types of renewable energy however, wind also has a cut off value, above which the turbines shutdown to avoid being damaged (GE Energy 2010; Raizada 2013). A typical wind speed and power production relationship is provided in Figure 1.

[4] One of the interviewees in Randall's dissertation cited that 80% of the market was based on speculative trading.

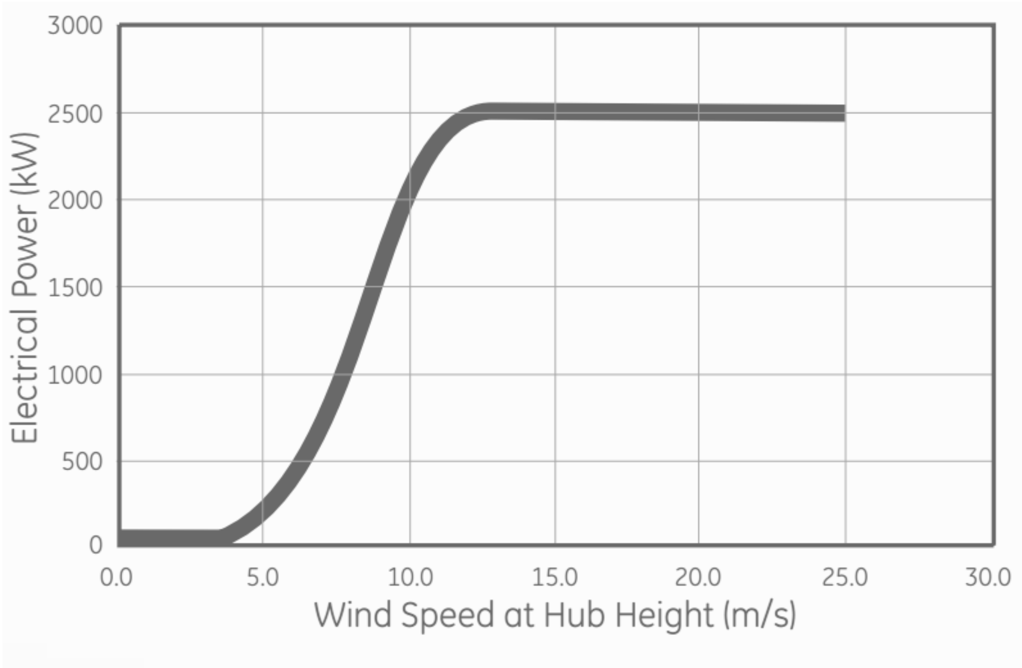


**Figure 1. Wind power curve. Image source: GE Energy 2010**

One of the risks associated with wind and solar power is this sensitivity to the variability in the weather. Hydro has better control over its power output. Variable weather means variable power production. This can create significant problems for the rest of the grid, as peak renewable power production is does not always occur at times of peak production. Improvements in techniques for wind and power forecasting have allowed grid operators to anticipate and partially compensate for changes in wind production by anticipating changes varying the output of other stations if necessary (Botterud *et al.* 2010). Still, some grid operators penalize power generators unreliable production, and under or producing at peak or off-peak times (Mitchell *et al.* 2006). Also the variability means that some years may bring in less revenue, making it difficult for operators to service their debt (Raizada 2012; Pérez-González and Yun 2013). The implications of these actions are discussed in more detail in the literature review chapter.

# 3. Literature Review

The topics of renewable energy investment, and risk management are both well studied in the peer reviewed literature. Research into weather derivatives, while scarcer, is also readily available. Although, the vast majority of that research is related to pricing models. However, at the intersection of these fields, while it is mentioned as a topic of interest, very little research has been conducted.

## 3.1 Investment

In order to understand what weather risk means for investment in renewable energy an understanding of the current state of investment in the industry is necessary. Investment decisions at their core is a balance of risk and returns. Investors usually prefer low risk and high returns (Wüstenhagen and Menichetti 2012). Given the choice of two portfolios with similar return, investors will prefer the one with lower risks. Wüstenhagen and Menichetti (2012), Dinica (2006), and Painuly (2001) all state that there is a high risk perception to renewable energy and that investment faces numerous obstacles.

In the renewable energy sector, the perceived risk and returns are in large part a function of government policy and subsidies (Wüstenhagen and Menichetti 2012). Therefore the level of investment in renewable energy in a particular area is dependent on the policy of the local government. This dependency on government policy adds risk in the form of political risk (Dincia 2006). There are of course many other factors influencing risk and return in renewable energy, such as the risk arising from new untested technologies (Mitchell et al. 2006; Economist Intelligence Unit (EIU) 2011; Masini and Menichetti 2013). However, currently, investment in renewable energy is still being driven primarily by subsidies and government policies (Wüstenhagen and Menichetti 2012).

One of the reasons why this subsidy is required is because renewables face economic and financial obstacles that put them at a disadvantage compared to traditional energy (Dinica 2006). This occurs for three main reasons. First, none of the calculations of the cost assessments for renewable energy or traditional energy include environmental externalities (Wüstenhagen and Menichetti 2012; Dinica 2006). Second, some of the cost assessment methods that have been used to evaluate traditional energy projects are simply inappropriate for renewable energy, making conventional projects seem cheaper than they actually are (Dinica 2006). Finally, investors tend to be much more conservative when adapting to new information (Wüstenhagen and Menichetti 2012),

Policies towards encouraging investment in renewable technologies appear to be working, Wüstenhagen and Menichetti (2012) note that recently private investment has become the largest source of capital for renewable energy projects. New technologies have a high risk perception (Dinica 2006), but more technologies are used and understood the less risky they appear. As the primacy of government intervention lessens in the investment decision-making process, additional factors affecting risk and returns will become more important, and tools to manage those risks will be sought (Carr 2013). Looking to the future, Painuly (2001) estimates that that over US$5 trillion of new investment in the energy sector will be needed to meet demands through 2040. The stakes are high as renewables need to capture some of this investment. Having tools that can manage some of the risks rising in importance related to renewable energy, like the weather, may have a positive impact on investment.



## 3.2 Volatility and risks

The weather on our planet varies significantly on numerous temporal and spatial scales. Volatility in rainfall, cloud cover, and wind speed can vary in minutes over an area of a few kilometers. Larger climate patterns can vary significantly over a few thousand kilometers. (McDaniel *et al.* 2014) While climatic shifts normally occur on a multi-decadal to century timescale or longer, recent anthropogenic climate change mean that these shifts are now occurring on a timescale relevant to industries and individual firms (IPCC 2001). As stated previously traditional energy firms are particularly sensitive to changes in weather patterns. Štulec *et al.* (2012) cited that changes in electricity demand and temperature had a correlation of over 0.95. Renewable energy firms are also concerned about changes in weather not just on the demand side, but also supply(Randalls 2006; Štulec *et al.* 2012). An Economist Intelligence Unit (EIU) (2011) report, sponsored by Swiss Re, states that wind volumes can deviate by 25% from historical values in a given year. Given the relationship between power output from wind farms and wind speed, see Figure 1 in the Background chapter, this 25% could have significant consequences for operators. This is reflected in the survey conducted by the EIU in the same paper (2011), with 66% respondents mentioning weather-related volume risk as a concern.

Numerous papers have examined and tried to quantify exposure of firms and the economy to weather risks (Pérez-Gonzáles and Yun 2013; Štulec *et al.* 2013; Lazo *et al.* 2011). Given the difficulty in finding specific plant output data for comparison, only papers that focused on comparisons to company revenue were used in this thesis. The method of calculating weather sensitivity in this paper looks at weather sensitivity on the firm level, more detail on this can be found in the Methodology section.

### 3.2.1 Wider Effects

In areas where there is a significant percentage of weather sensitive renewable energy feeding into the grid, this weather-related supply volatility can also impact the wider electric grid (Parsons *et al.* 2006). The price of electricity in deregulated markets is determined by supply and demand. Renewable energy production does not necessarily correlate with demand, and spikes in renewable production can cause major changes in the electricity market. Numerous interviewees had stories involving the effects of renewable energy on spot prices and traditional energy companies. The literature does mention that the volatility of renewable energy has an impact on the wider energy grid (Parsons *et al.* 2006). However, how this impact is managed on a system-wide level can vary significantly depending on the energy policy of the countries involved

(Mitchell *et al.* 2006). Mitchell *et al.* (2006) gives a good example of this in their comparison of UK and German renewable energy policy. Germany gives renewable generators a special tariff over the market price of wholesale electricity, while also giving them priority feeding into the grid. The UK, also gives renewable generators priority, but additionally has a system in place that effectively penalizes intermittent generators by forcing them to pay a penalty for under or over generating (Mitchell *et al.* 2006).

## 3.3 Impact on Business

Exactly how weather risk and the volatility associated with it affects the performance and investment within energy companies has been examined in a couple papers for traditional energy companies and more 'conventional' demand-side temperature risk (Pérez-Gonzáles and Yun 2013; EIU 2011). The Swiss Re sponsored report by the EIU (2011) outlines two possible ways weather risk can affect company profits. Pérez-González and Yun (2013) provides a more detailed explanation of how weather derived volatility affects firm valuation, as well as a very interesting quantitative analysis on how the use of temperature derivatives affected the financial situation of the firms that started using them in the 1990s.

The EIU (2011) report gives two examples of weather risk, consistent shortfall and volatility. Consistent shortfall means that expected plant output will generally be less than expected for the lifetime of the project, resulting in smaller overall revenue. Given the short time frames on which weather derivative contracts are typically written for (Randalls 2006; Pollard *et al.* 2008; Brockett *et al.* 2005) it is unlikely that they would be able to provide adequate cover for this outcome. The cause of this type of risk is more likely to arise in the planning phase, for example, inadequate or inappropriate weather data (EIU 2011), but it could also be due to climate change (Cradden 2009)[5]. The other weather risk outlined by the EIU (2011) report is volatility. That is, the expected output for the lifetime of the plant is met, but with huge variations for any given day, month, year, etc. In periods of low generation, and therefore low revenue, the debt that was used to finance the project must still be serviced, which can cause financial hardship (Pérez-Gonzáles and Yun 2013; EIU 2011; Raizada 2013). It is this volatility example that weather derivatives seem to be well suited to deal with, as they can provide supplemental income during years of hardship.

Pérez-González and Yun (2013) take this observation a step further, by analyzing conventional energy companies in the US who are exposed to weather risks and comparing firms that decided to use weather derivatives starting in 1997 to those that did not. They explain that in order to protect investments and be able to service their debt in hard years, companies exposed to weather volatility must have lower leverage, more cash on hand and lower debt levels. This has a negative impact on firm value. During their analysis they found that weather exposed firms were less valuable and adopted more financially conservative policies. Their comparison also found that weather derivatives "have a statistically significant and economically meaningful effect on profits for weather-sensitive firms" (Pérez-Gonzáles and Yun 2013). Overall, weather derivatives had a positive effect on firm value, most relevant here is that the use of weather derivatives allowed them to increase their debt capacity and invest more(Pérez-Gonzáles and Yun 2013).

The analysis done in Pérez-González and Yun (2013) looked solely at conventional energy companies, and only at the demand-side volumetric risk caused by temperature volatility. A similar quantitative analysis for the effects of weather derivatives on renewable energy firm value has not been done. Unfortunately it would be very difficult to replicate this study for the renewable energy sector and for a risk such as wind or solar for two reasons. First, Pérez-

[5] This thesis study region was the UK and it concluded that the change would be small enough not to require strategic changes, but it would have some minimal impact on volume and perhaps seasonal pricing.

González and Yun (2013) used publicly available financial and operating data for the energy companies. This data is much scarcer in the renewable energy sector, and even for public companies very rarely do their annual reports explicitly mention when they are specifically hedging supply-side weather risk (wind/solar/rainfall) versus demand-side (temperature) or other weather risk. In addition, the relationship between energy production and wind/solar/rain risk, while still strong, is more complicated than it is for the fairly linear relationship between temperature indexes and energy demand.

## 3.4 Risk Management Strategies

The literature describes various methods by which companies can deal with these risks. Štulec *et al.* (2012) ranks four general risk management options in order of effectiveness: avoidance, acceptance, reduction, and transfer.

The volatility in weather is taken into consideration during the planning and site selection process for new renewable energy installations (EIU 2011). Firms would prefer to avoid building plants in areas of low potential production or excessively high volatility in the first place (Štulec *et al.* 2012). In the planning process they take into account both the historical average averages and consider the potential for the weather to deviate from these averages(Štulec *et al.* 2012). By not building plants in high risk areas to begin with they are able to avoid exposure to volatile weather.

The next method described by Štulec *et al.* (2012) is acceptance of losses. This method is implicitly invoked whenever managers take no other risk management strategies and attribute changes in revenue to the weather. For many industries with weather risk exposure this seems like the option most often used (Štulec *et al.* 2012; Myers 2008). The Weather Risk Management Association (WRMA) would like to have this option seen as irresponsible among the business and financial communities (Randalls 2006). Randalls (2006) describes how they have lobbied to have management of weather risks taken into consideration by credit bureaus. This was met with limited success, Randalls (2006) mentions that while there are examples of companies being praised by credit bureaus for their weather risk management strategies, no company has been penalized for lack of management.

The reduction option involves finding natural hedges in other projects to offset the risk of a single operation (Štulec *et al.* 2012). This is called diversification and it is mentioned by numerous papers as a way of dealing with weather risk (Wüstenhangen and Menicehetti 2012; Štulec *et al.* 2012; Pérez-González and Yun 2013; EIU 2011). It is also a common risk management method used by investors to reduce the overall risk of their portfolios (Wüstenhangen and Menicehetti 2012). By placing plants in various locations, or using many different technologies, it reduces the risk of a single weather event significantly impacting the firm. This method has the advantage that the company does not need to pay premiums for coverage (Štulec *et al.* 2012). However it is not actually removing the risk, just reducing the overall impact of a single risk on the firm. Diversifying spatially does have some downsides. The plants would need to be placed very far apart, maybe even on the order of 1000s of kilometers apart, the size of synoptic scale meteorological events (McDaniel *et al.* 2014), in order to significantly reduce the correlation in weather between the two locations. In addition, according to Pérez-González and Yun (2013), the economies of scale that make construction cheaper are higher in nearby communities, which experience similar weather conditions, which may make diversification strategies more expensive. The EIU (2011) report also states that larger companies have a better ability to diversify, than smaller ones.

Pérez-González and Yun (2013) mention a few strategies that fall between the reduction and transfer options outlined by Štulec *et al.* (2012). This includes investing in technology that can adapt to changing weather conditions and battery storage technology. They also mention how energy companies can use 'weather normalization adjustments' to recuperate income lost from bad weather, however that method is not available in deregulated markets, where energy firms are most exposed to weather risk. Both Pérez-González and Yun (2013) and the EIU (2011) report state that long term service contracts are commonly used to mitigate this risk, which could also be seen as a type of risk transfer. As energy markets deregulate it is conceivable that the 'normalization adjustments' will be replaced with more market friendly risk management strategies.

The fourth option listed by Štulec *et al.* (2012) is transfer, which involves moving the financial burden of risk to another party by means of insurance, commodities, or derivatives. As stated previously in the Background chapter, traditional insurance coverage is not an option for covering this type of risk. The possibility of not producing as much electricity as anticipated due to changes in weather is considered part of the risk of doing business for renewable plants, and won't be covered by insurance companies by traditional products (IRMI 2014). However, insurance companies/re-insurers are also major sellers of OTC weather derivatives products. Many papers and articles mention the potential for derivatives to deal with weather related volume risk in renewable energy (Randalls 2006; Štulec *et al.* 2012; Raizada 2013; Carr 2013) and there are many examples and documented cases of how they have been used by traditional energy companies to manage their demand risk, so it is possible (Pérez-González and Yun 2013; Belakovskaia 2014; Randalls 2006; Brockett et al. 2005). However, only one paper gives a figure on the current state of the market for renewable energy. The EIU (2011) survey found that only 1% of survey participants utilized financial derivatives to manage weather related renewable generation volume risk, and just 3% anticipated using them in the next three years. The terms of these small number of contracts, their effectiveness, and their impact on investment is unclear. While a recent major rainfall contract is public knowledge (Yahoo Finance 2014).

## 3.5 Weather Derivatives Market

The current state of the weather derivatives market is hard to determine. The most visible side is the CME Group's weather derivative exchange that publishes prices, contract terms, and some market data. Unfortunately, most of the underlying weather values for contracts on the exchange, like temperature, are not useful for dealing with supply-side weather risk. In addition, the standardized exchange driven contracts are a minority of the contracts traded worldwide. Most contracts are custom made and traded over the counter (OTC), with only the buyer and seller having knowledge of the deal (Pérez-González and Yun 2013). This makes most of the workings of this market very opaque. WRMA, the industry association formed to "enhance public awareness of the weather risk industry and promote the growth and general welfare of the weather risk market", does perform surveys on the current state of the market (WRMA 2014). However, this report is only available to WRMA members.

Over the years since this product's inception several research papers on the state of the weather derivative market have been publish, (Randalls 2006; EIU 2011; WRMA 2014; Pérez-González and Yun 2013; Alexandridis and Zapranis 2012) a few even include interviews or surveys with industry participants. Some papers are somewhat dated, some contradict each other, and only one of the papers reviewed included any information on the renewable energy market. Fortunately, from these reports I was able to gleam some information about the workings of this market and how actors behave in it.

The study conducted by Pérez-González and Yun (2013) found that traditional energy firms in the United States that were highly weather exposed were two to three times more likely to use weather derivatives once they became available in 1997. Specifically, in the segment of the market that could be used by renewable energy, a paper by Alexandridis and Zapranis (2012) stated that wind derivatives specifically were extensively traded in the electricity sector. This assertion is interesting given that the EIU (2011) report published only a year prior state that interviews were anticipating greater availability of products related to things like wind. In fact, the EIU (2011) survey found that 32% of respondents used some sort of "weather protection providers (e.g. financial hedging instruments)" as part of their risk management strategies, but only 1% used financial weather derivatives. Interviews conducted as part of this research also challenge the assertion that there is a heavy emphasis on wind-related trades, or at least question for what purpose those hedges are used.

The organizations involved in the weather derivative market include investment banks, reinsurance companies, hedge funds, dedicated brokers, utility companies, speculators and others (Belakovskaia 2014; Brocket *et al.* 2005; Randalls 2006). Utility companies in a particular service area are exposed to very similar risks, so it is unlikely that there will be enough utility companies with opposite risks to balance those who want to buy and those who want sell. Investment banks, hedge funds, and others are needed as counter parties to many of these contracts. Speculation, within exchanges, while it does engender very negative connotations for people, provides liquidity to the small weather derivatives market. A snowfall contract on the CME Group exchange was discontinued because no one wanted to buy (Gandel 2014). Having liquidity in the market means that when someone wants to trade, a counter-party is available to complete that transaction.

The attitudes of the papers writing on this topic are that these derivative contracts, for all types, not just for renewable energy, have potential, and that the market is slowly growing. Lack of access could be one potential handicap to growth, as a certain financial conditions must be met in order to trade in these products (Randalls 2006; Vortex Insurance Agency 2009). On top of that the pricing mechanisms and construction of many of these contracts is extremely complex. Temperature is a straightforward metric to build a statistical model around for a particular station (Štulec *et al.* 2013). Wind on the other hand is more complex, requiring a more sophisticated model (Alexandridis and Zapranis 2012) that needs to be reliable and trusted by all stakeholders. The news article by Raizada (2013) cited comments from a weather derivative provider that, with wind, buyers are also concerned about the basis risk between the location of the wind turbines and the nearest available weather station.



## 3.6 Previous work on weather derivatives and risk management

Štulec *et al.* (2012) reference a paper that argues that weather derivatives are "the most effective instrument of production against adverse weather", however there is still hesitation among potential users (Alexandridis and Zapranis 2013). This may be due in part to the hesitancy of investors, and presumably risk managers, described by Wüstenhagen and Menichetti to incorporating new information. There has been one previous study found that looks at the relationship between weather derivatives and renewable energy financing, a feasibility study in Mexico (Fadhl *et al.* 2008) on how using weather derivatives could be used to improve the financing conditions of renewable energy projects, and maybe accelerate renewable energy expansion.

### 3.7 Framework

The primary objective of this thesis is to examine how investment in renewable energy can be impacted by managing the risk associated with the variability in the weather. It is therefore useful to have a conceptual framework of renewable energy investment through which to examine the relationship between weather risk, weather derivatives, and investment. Wüstenhagen and Menichetti (2012) provide such a model, which will serve as the basis for analysis during this research.

Wüstenhagen and Menichetti took the basic model of risk and return for investment and expanded on it. This basic model says that investment in renewable energy is dependent on the risk and returns of the project, both of which are affected by energy policy. The expanded model states that it is perceived risk and return that matter. Actual risk and return is filtered by individual investor's position in the marketplace as well as their previous actions and investments. All of these aspects are influenced by government-level energy policy. Diverging from the basic model even further, in this new model the level of investment is not even directly determined by perceived risk and return, but the potential positive effects of portfolio diversification must also be taken into account. Figure 2 shows a diagram of their model. This expanded framework allows for a more detailed discussion that can better explain how weather derivatives may affect investment. This model has the added benefit that is can be generalized to

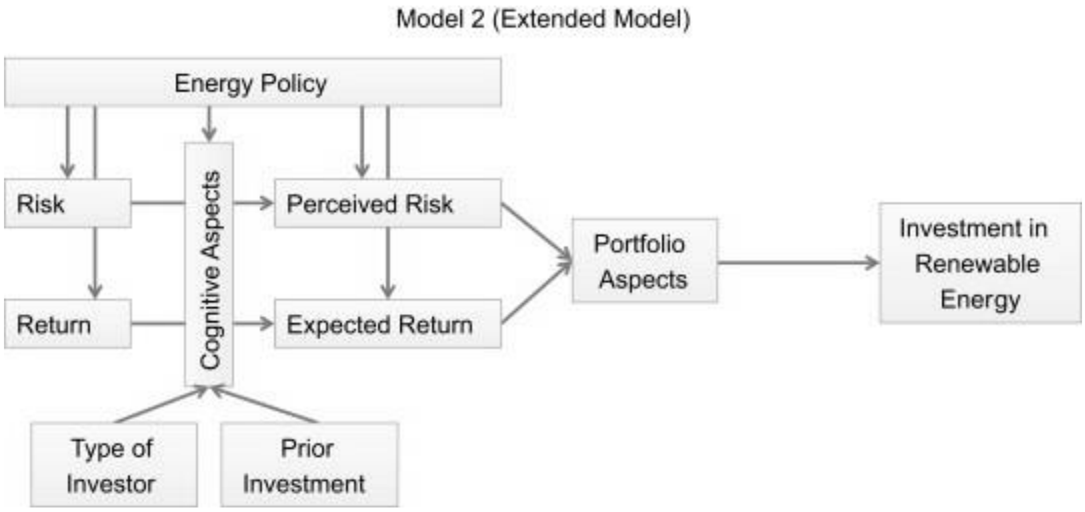


**Figure 2. Framework for renewable energy policy and investment. Image source: Wüstenhagen and Menichetti 2012**

explain the decision making process of whether to 'invest' in weather derivatives, or not.

The literature has not used this framework in this exact way previously. Most papers citing Wüstenhagen and Menichetti (2012) incorporated their investment conceptual framework into a larger qualitative or quantitative model as part of the representation of the actions of investors (Fagiani *et al.* 2013, Möller *et al.* 2012, Lüthi *et al.* 2012). These larger models were used to evaluate or recommend policy measures, or to create tools to help model or demonstrate policy effects. The objective of the framework and the paper was to provide a model that explains the "…underlying strategic choices for renewable energy investment, and how they are influenced by energy policy" (Wüstenhagen and Menichetti 2012). Rather than analyze how energy policy influence renewable energy investment, the intent here is to use this model to analyze how weather derivatives affect risk perception and other aspects of the strategic decision making process. Given this framework's history of being used to drive the decision making process of investors, this use of the model seems reasonable.

The analysis of weather derivatives though this framework should apply to any energy policy regime. However the discussion section will go into more depth about the possibility of regulatory regimes to influence the effectiveness or desirability of weather derivatives. A comparison of English and German policies as described in Mitchell *et al.* (2006) is used for this purpose.

The same volume in which this conceptual framework was published also included another conceptual model of the renewable energy decision making process (Masini and Menichetti 2012). This model is not used here because it focuses more on investor preferences and policy. This risk and return model on which Wüstenhagen and Menichetti's framework is based is much more appropriate for evaluating the impact of a risk management product on investment. However, both of these frameworks are somewhat incomplete when it comes explaining internal investment within a company, say for new capital projects. In these cases the current financial situation of the firm also needs to be considered, which for energy companies is also sensitive to the weather (Pérez-Gonzáles and Yun 2013). The literature review provides an overview of Pérez-Gonzáles and Yun's (2013) explanation for how firm value, cash levels, and debt can impact investment. This additional information may be necessary to adequately explain the responses collected from the interviewees.

# 4. Methodology

Weather derivatives are complex financial products traded in an obscured market that can be used and written in a variety of ways, and the renewable energy sector is a diverse, dynamic, and growing industry. Examining how the weather affects the renewable energy sector, as well as how, and the potential for, weather derivatives to improve the risk profile and investments in renewable energy requires a variety of approaches. Three research methodologies are used in this thesis, quantitative analysis, interviews, and a review of annual reports. The data collection process was a difficult one, and because of that each of these analysis are lacking in some way. The idea is that the use of these three techniques will complement each other and provide a clearer picture of the weather derivatives market and how this product can effect investment in renewable energy.

## 4.1 Obstacles

As stated in the literature review, the majority of trades in weather derivatives occur over the counter (OTC), rather than on an exchange. These OTC products as well as the risk management strategies utilized by energy companies are considered proprietary information. In addition, the weather derivatives market is extremely small compared to other derivative markets, and the portion of this market that serves, or could potentially serve, the renewable energy sector is a tiny portion of the weather derivatives market. These factors created significant problems for conducting research in this area. Limited peer reviewed literature, numerical data availability problems, a limited interviewee pool, and lack of interest from critical parties were the most significant obstacles encountered during the course of this project.

Many of the problems of researching in this field have been well documented, most comprehensively in the PhD thesis of Dr. Samuel Randalls who wrote on the UK weather derivatives market. The methodology used here for data collection is based in large part on his experiences and methodology, especially for interviews.

Randalls noted 3 reasons for being denied interviews. During his research many subjects were either too busy, couldn't be bothered, or were concerned about confidentiality. Issues surrounding confidentiality was a recurring theme in the methodology section of his dissertation, affecting not only who he interviewed, but also what they said and the method of recording used. The methodology and fieldwork here was done with this paper in mind.

## 4.2 AMS Annual Meeting

The first half of the literature review for this project initially turned up very little information on the current state of the weather derivatives market, or the specific details on how these products worked. In order to gain more up to date information on the workings of this market I attended the American Meteorological Society's 2014 Annual Meeting in Atlanta, GA, USA, specifically, a short course entitled 'Weather to Risk it or Not: The Fundamentals of Weather and Risk Management'. This course and the associated energy conference provided invaluable information on some of the current workings of the market in the United States, as well as enthusiastic and knowledgeable contacts.

The short course provided information risk about weather risk in general including models used, as well as how decision makers perceive and react to risk. In addition it introduced the background of the weather derivative market from some of the actors who were present at its inception. Finally, it gave insight into how weather derivatives are used, for example an 'ideal' winter hedge, how to read CME Group ticker information, and the types of weather derivatives that are out there. All of the official proceedings of the both the short course and the annual meeting were recorded and publically available. Any information obtained from these events will be appropriated cited.

The conference itself also yielded extremely helpful contacts. During the conference I was able to have brief, casual conversations with both speakers and participants about weather risk management, derivatives, and areas that they felt needed additional research. I took several people up on their offer to continue the conversation via email after the conference. These conversations, while they did not always provide data useful to this thesis, undoubtedly helped shape the direction this research took.

## 4.3 Quantitative Analysis

Access to quality numerical data for analysis was a significant problem. A variety of different sources were queried for meteorological, financial, and weather derivative market data, all with limited success. The amount of data obtained limits both the types of analysis that can performed and the relevance of the results. However, some quantitative analysis is desirable so as to give some indication as to potential of this market.

Thomson Reuters Eikon, Thomson ONE Banker, and the CME Group website were all used to access corporate financial and weather derivative market data. I was able to acquire the financial data of 52 publicly traded 'alternative energy' companies operating in Europe dating back 10 years. Historical CME Group data was not available given the access privileges of the accounts available to me. However, CME has few contracts that are potentially relevant to managing the supply side risk of renewable energy. Also unavailable is information on the OTC market for weather derivatives. These contracts aren't public knowledge, however there was a survey done by WRMA on the OTC contracts completed by its members. Unfortunately, a request for the most recent survey were denied, however aggregate survey results prior to 2006 were available, and some qualitative information from the report was provided by interviewees.

Meteorological data was significantly easier to obtain than financial data, however it was not without its challenges. Weather data in many countries is not freely available, however for the type of data required here, surface observation data, there is usually a free option available. German surface observation data was obtained from a section of the meteorological office site, and UK surface observation data access was granted after submitting a research proposal to the

British Atmospheric Data Centre (BADC). The interview portion of this project also revealed that, contrary to some of the literature, many weather derivative suppliers now trust and utilize model reanalysis data (Zheng 2000)[6]. Therefore, I also obtained data from ERA-Interim, a European Centre for Medium-range Weather Forecasting (ECMWF) reanalysis project.

Based on the data available and the time limitations of this thesis, I ultimately decided to try and adapt part of Pérez-Gonzáles and Yun's (2013) methodology for calculating weather-induced volatility on firms to renewable energy using the revenue data obtained from the public companies in Europe, and the ERA-Interim project. This analysis involves comparing the income of companies to the change in weather over the area in which they operate. This could show how much of the fluctuations in a company's revenue is due to certain meteorological events.

For the meteorological data side of the calculations ERA-Interim was chosen over the recorded surface data because of its ease of use and trustworthiness among those in the weather derivative community (See Results). The use of surface data would have necessitated identifying the most appropriate stations for each renewable installation for every company, as simple areal averaging would have introduced unnecessary complications and biases (unequally spaced stations, etc). It also would have limited the analysis area considerably. ERA-Interim has global gridded data and has already interpolated data points for where there are no weather stations, greatly expanding the area that can be analyzed. While the surface observation data won't be used I still owe a debt of gratitude to the BADC and German met offices for providing this information free of charge.

Any attempt to analyze the effectiveness of weather derivative on renewable energy companies without actual performance data would have required modeling. Given the limited

[6] One of the problems in using raw weather station data is that stations are unevenly spaced, with many readings in some areas and few readings in remote areas. This data can also be difficult to read into weather and climate models. What reanalysis does is assimilate all surface observation, satellite, sounding, radar, and other data into a computer model of the atmosphere. It then interpolates what the weather was probably like in areas on the earth that we don't have measurements, providing a nice, gridded, continuous set of historical meteorological data in space and time.

data available, the utility of such a model did not justify the time and effort required to build it. The correlations between income volatility and weather induced volatility are easier to calculate and can provide a rough illustration to the potential level of weather exposure of firms in Europe. This analysis uses significantly fewer data than Pérez-Gonzáles and Yun (2013), and they warn that this correlation should be treated with caution. A footnote for this section reads,

> …whether firms with higher revenue volatility have higher covariance between weather and revenue variables is determined by whether higher revenue volatility is driven by weather or other factors. For example, high revenue volatility that is explained by non-weather-related variables leads to unchanged weather betas [see next paragraph] and lower revenue-weather correlations. Intuitively, higher revenue volatility does not necessarily imply higher gains from hedging weather exposures as measured by weather betas. (Pérez-Gonzáles and Yun 2013)

The revenue of the companies in question is undoubted influenced significantly by factors other than weather. The companies in this analysis are most likely more diversified than the companies Pérez-Gonzáles and Yun were looking at for their pre-1997 analysis meaning revenue and income are affected by more factors. These companies all operate over different geographic ranges. Extracting the geographical extent of each of these companies is too time consuming so the average over Europe is used. At least some of these companies also have weather exposure outside of this area, meaning the study area may leave out some weather sensitivity. This averaging also washes out the spatial variability of weather within Europe. Gross income is used here rather than revenue, because total revenue was not readily available to download in bulk.

Pérez-Gonzáles and Yun estimated weather exposures using two measures, volatility of quarterly revenue, and a value called the quarterly weather-induced revenue-asset volatility. Since only access to the annual income data was available, annual averages were used for both weather and income values, with the calculation of the historical standard deviations of weather values. Of course this does smooth out some of the volatility companies experience. The volatility of income here is defined to be the standard deviation of the annual income (Investopedia 2014d), the authors did not define revenue volatility in their paper, but said it was 'straightforward to compute'. The weather-induced income-asset volatility is represented by weather 'betas', which are the coefficient of the following regression,

$$incomeassets = \alpha + \beta * weathervalue + \gamma * \ln(assets) + \epsilon$$

Where *incomeassets* is the annual income to assets ratio, the *weathervalue* term is the appropriate weather index, and the fourth term controls for differences in the levels of assets between each company (Pérez-Gonzáles and Yun 2013).

First, ERA-Interim wind speed, total rainfall, and total cloud cover data obtained from ECWMF in Network Common Data Form (NetCDF) form were processed by the scripts and NCL programs[7] shown in Appendix I, as well as through the manual entry of commands. These scripts utilized NetCDF Operators to calculate the magnitude of wind speed, and find the areal average of these values over Europe. NetCDF is a common data format in the atmospheric sciences for storing climate and weather model data. Yearly averages were calculated for wind speed and cloud cover, and annual totals were calculated for rainfall. The standard deviations for the weather values were calculated from the entire times series. There was a statistically significant trend significant trend in the total cloud cover and precipitation series, this was removed prior to the standard deviation calculation. These calculations and a more detailed discussion on this can be found in Appendix II. No transformations were made to the annual meteorological data, or to the financial data.

The gross income to asset ratios, the natural log of assets, and the volatility of income were all calculated in Microsoft Excel. Some companies has less data available than expected,

[7] NCL is the NCAR Command Language, a programming language developed at the National Center for Atmospheric Research in the United States specifically for the scientific data processing and visualization.

companies with fewer than 4 data points in the 10 year period were eliminated. For simplicity linearity between the variables was assumed, however this may not be the case. The last portion of the analysis including the multiple 'linear' regressions, and the correlation between 'weather-induced volatility' and revenue volatility was calculated in a python program that can be found in Appendix III.

## 4.4 Interviews

Given the limited number peer reviewed articles, the extreme difficulty in accessing market data, and the proprietary nature of corporate risk management strategies, interviews were necessary to gain any meaningful understanding of the weather derivative market for renewable energy and the implications of using weather derivatives. Interviewing is a common methodology for obtaining qualitative data. Interviews at this stage of the research took a variety of forms and were generally semi-structured interviews (DiCicco-Bloom and Crabtree 2006), but some interviews were conducted via email. The exact methods of contact included phone calls, emails, Skype, and in-person interviews.

All interviewees received a basic overview of the topic of the thesis in the initial contact. Since a large number of interviewees in Randall's dissertation (2006) were concerned about anonymity and confidentiality, and from my own impressions from initial contacts with conference participants, anonymity was promised to all interviewees. In addition, interviewees were given a choice whether or not they wanted to be recorded. Randalls (2006) noted that "…much of the most interesting material was presented when the tape-recorder was switched off…". I also found that during some interviews the conversation continued for longer than the recording, offering very helpful and thought provoking details. For this reason notes supplemented the recorded conversations. Some interviews were contingent on not being recorded. One interviewee was more than willing to have an informal talk, however in order for me to record they said they would need to consult with their supervisor or legal department.

While recording provides a great record of the interview that can be referred to later, having access to the information interviewee can provide is most important. Hand written notes are still able to capture the major points of the conversation.

While only a small percentage of those contacted responded, even fewer actually agreed to be interviewed. The interview sampling was done in a way similar to that described in Coyne's (1997) section on sampling in the initial stages of a study. People and organizations were contacted based on my perception of the information and insights they may have on this topic. This was assisted by the knowledge gained at the AMS Conference. In addition, the WRMA member list, and companies listed in the EIU report (2011) were used to find individuals to contact. All in all 50 companies and individuals were contacted for interviews. Renewable energy companies, large traditional energy companies with renewable assets, consulting firms, law firms, insurance/re-insurance companies, specialized weather risk management companies, manufacturers of renewable installations, and data providers were all contacted by either phone or email. The majority of contacts/companies were chosen based on their work or background, and a handful were provided to me by other contacts. The ultimate goal was to get a cross section of all actor types involved in this area. Also, occasionally, specific questions in email interviews were forwarded on to others. Depending on the number of responses received the 'saturation principle' (Schoenberger 1991) would be applied to interviewee categories. This is the principle that there is no reason to continue interviewing when the responses are continuously repeated. This was not achieved in most of the interview categories, but given the small population it may have been achieved in the weather derivative provider category. Unfortunately, there was a significant skew in the responses towards weather derivative providers which will be talked about further in the results and discussion sections.

The initial response rate to emails and cold calls was fairly high, with 26 out of the 50 individuals and companies contacted replying back to me at some point. Unfortunately, out of those 26 only 10 were interviewed. From the pool of 10 interviews, 4 were interviewed by email, 3 were interviewed in person (2 recorded, 1 with handwritten notes), and 3 were interviewed via Skype (2 recorded, 1 with handwritten notes). Email interviews were the shortest with 1-3 interactions over the course of a few days or weeks, usually providing 2-4 paragraphs of responses. Skype interviews lasted 20-30 minutes, and in person interviews were the longest, lasting between 40 minutes and an hour. A list of the anonymized participants, and the way in which they were interviewed is provided in Table 4.

**Table 4. Anonymized list of interview participants**

| # | Title | Company Type | Interview Type | Recorded? |
|---|---|---|---|---|
| **1** | CEO | Renewable Energy Seller | Email | N/A |
| **2** | Weather Derivative Team Lead | Electric Utility – Trading Division | In-Person | Y |
| **3** | Originator | Re-Insurance Company | In-Person | Y |
| **4** | Executive Director | Non-Profit specializing in investment risk | Email | N/A |
| **5** | Partner | Insurance Broker | Skype | Y |
| **6** | Analyst | Energy Trading Company | In Person | N |
| **7** | CEO | Meteorological Data and Software Supplier and Consultancy | Skype | N |
| **8** | Consultant | Wind Modeling Company | Email | N/A |
| **9** | Advisor | Environmental Investment Firm | Email | N/A |
| **10** | President | Renewable Energy Development | Skype | Y |

The remaining 16 declined for a variety of reasons. Most common was that they did not believe they had enough knowledge or background to assist in this research. This is most likely due to the way in which initial contact was made with these individuals. For all participants I explained the focus of this project was examining the ways in which weather risk management, with a focus on weather derivatives, could affect the revenue of renewable energy installations and investment. I believe this focus on weather derivatives in the initial communication scared away many potential interviewees. Adjusting my introduction for later contacts to focus on general investment risks for renewable energy, and then talking about weather derivatives or similar hedges returned much more positive and helpful responses. One sent brochures as a response. A couple more stated they did not have the authority to release the information I requested. Three responded positively for interviews, however time constraints did not allow me to conduct those interviews.

Three of interviewees were on the seller side of the weather derivative market, and one was a provider of data, software, and expertise for weather derivative contracts. These individuals provided the most information out of all those contacted, constituting four out of the six verbal interviews conducted. This obviously adds some bias to the data collected, in favor of weather derivative products as an effective tool to hedge against non-catastrophic weather risk. There were also two interviewees related to finance, although both were involved in the same email chain. One energy trading company, one energy reseller, one renewable energy developer and one wind modeling company. For all 6 of these interviews the discussion was renewable energy risk with a focus on the weather. Many were unfamiliar with weather derivatives, or they never came up when discussion risk management strategies.

Sample interview questions are provided below in Table 5, these are not the exact questions but provides a nice overview of the different questions asked to various interviewees.

**Table 5. Sample Interview Questions**

- How concerned does the market seem to be about supply-side variability due to weather of renewable energy?
- Where do you think the market is headed?
- Are you aware of any studies or resources available looking at the effectiveness of these products? Or data on this market?
- Are these products used regularly?
- Are you aware of any companies in the UK or Europe who are using wind or other OTC weather derivatives to manage supply risk in renewable energy?
- How does weather variability affect the power market in general?

The questions varied from participant to participant because there were no two interviewees that had the exact same background, or relationship to the weather derivatives or renewable energy market. Many questions had company specific components to them. When conducting in-person or Skype interviews, the techniques outlined in Seidman (1998) were used.

All contact with individual interviewees was then compiled together and coded to find common ideas and themes. The open coding methodology was loosely followed for this procedure (Strauss and Corbin 1998). For suppliers of weather derivatives, particular focus was paid to comments about specific use of derivatives by those active in the renewable energy sector, or who is using derivatives that could be used by the renewable energy sector (i.e. wind, rainfall, etc). The focus for investors and operators was more general risk management strategies and techniques. Another theme that was central is the current, and potential future, of the market. The full list of themes and topics discussed can be found in Table 6.

**Table 6 Themes and topics used in coding**

1. Investment
   a. Is weather variability a concern when considering investments in renewable energy?
   b. Investment buffer/margin
   c. WX Derivatives built into financing
   d. Debt providers/amount
2. Derivatives Contracts
   a. Data Quality/Availability
   b. Length of contracts
   c. Counter parties
   d. Index, contract construction
   e. Price of contracts
3. Derivatives Market
   a. Size of overall weather derivatives market
      i. Problems determining market size
   b. State of the market/evolution
   c. Weather derivatives market (for renewables)
   d. Secondary Market
   e. CME Group
   f. Liquidity
   g. Comparison to other markets
4. General Risk Management
   a. Steps to hedge against output for new installations/investment
   b. Risk retention
   c. Hedging in operational installations (renewable)
   d. General hedging techniques
   e. Diversification
5. Stories, background, and speculation
   a. Stories about risk management and general derivative use
   b. Stories specifically about renewable energy or renewable contracts
   c. Reasons wx derivatives aren't being used for renewables
   d. Wider effects of volatility on electricity market
   e. Alternative users for wind/rain/solar derivatives
6. Other
   a. Wind Manufacturer
   b. Climate Change
   c. Developing Countries
   d. Other sources of information
   e. Confidentiality
   f. Regulation
   g. Other

## 4.5 Annual Report Review

Due to the lack of response from energy companies and other potential users on the demand side of the weather derivatives market, I also reviewed the latest annual reports for 6 companies in the UK. I analyzed where and how they prioritize non-catastrophic weather risk, as well as what their strategy was for managing that risk. While these are not unbiased sources, they are subjected to the same confidentiality concerns that limit interview respondents and the hope is that they will provide a better understanding of how companies as a whole perceive weather risk. Specifically, when reviewing the reports I was looking for answers to three questions:

- Are they concerned about non-catastrophic weather risk? If so, what types?
- How to they prioritize this risk?
- What methods of risk management do they employ to deal with weather risk?

The information gathered from these documents was analyzed using an open coding technique similar to the one used in coding interviews.

# 5. Results: Energy exposure to weather risk, use of weather derivatives, and potential impacts

This chapter is a guided presentation of the data collected under the research methodologies described in chapter 4. The quantitative analysis is presented first followed by a breakdown of the interview results by coding theme, and finally the analysis of the annual report review.

## 5.1 Quantitative Analysis Results

The purpose of the quantitative analysis is to illustrate the relationship between variability in weather and variability in income. Given the relationship between weather variables and power production for individual renewable energy plants, and my assumption that this risk is not being adequately managed, I expected to see an effect on the aggregate of these plants at the company level.

The results of the quantitative analysis are inconclusive. The small sample of companies, the relatively short timeframe, lack of sub-annual data, significant averaging of meteorological data, and the large number of factors on income most likely all contributed to this result. The numerical results showed very little correlation between cloud cover, wind speed, total annual precipitation and income volatility. This could mean that this risk is not actually significant, that it is well manage, other factors affecting revenue are significant more influential, that the relationship between these values is not linear or any number of things. These interpretations should be taken with a grain of salt as the confidence on these numbers is quite low.

The results of the statistical analysis can be found in Tables 7 and 8. These tables are meant to mimic Table II Panels A and B respectively from Pérez-Gonzáles and Yun (2013). Table 7 contains the descriptive statistics on the calculated variables used in the correlation. Standard deviation was not included because the same Europe-wide standard deviation was used for all companies. Table 8 contains the correlations between the weather induced volatility terms and income volatility, as well as with themselves. The python Pearson correlation coefficient function provides a built in a 2-tailed p-value, but this is not shown here because it is unreliable for smaller datasets (The Scipy community 2013). A test for normality was performed because a normal distribution is an assumption of the Pearson correlation coefficient (The Scipy community 2013). The test returned that there was a high probability that none of the variables were normally distributed.

**Table 7. Descriptive statistics of measures of volatility**

| Variables | N | Mean | Std Dev | Min | Median | Max |
|---|---|---|---|---|---|---|
| **Income Volatility** | 44 | 97.339 | 331.031 | 0.000 | 7.394 | 2116.543 |
| **Cloud Beta** | 45 | 1.859 | 1.851 | 0.000 | 1.384 | 9.348 |
| **Wind Beta** | 45 | 162.188 | 186.586 | 0.000 | 109.519 | 854.051 |
| **Precip Beta** | 45 | 5.892 | 13.232 | 0.000 | 2.934 | 89.053 |
| **Cloud Weather Induced volatility (Beta*Std Dev)** | 44 | 0.170 | 0.173 | 0.000 | 0.122 | 0.868 |
| **Wind Weather Induced volatility (Beta*Std Dev)** | 44 | 0.173 | 0.202 | 0.000 | 0.117 | 0.914 |
| **Precip Weather Induced volatility (Beta*Std Dev)** | 44 | 0.000 | 0.001 | 0.000 | 0.000 | 0.006 |

This lack of normality is not particularly surprising as this was not a random sample, but a time series. Bootstrapping, another other re-sampling method, or some form of distribution fitting may have all been able to correct or mitigate the problem, but time limitations did not allow me to redo these calculations. There may also have been trends in the income data, but, at least in the multiple regression calculations, this should have been corrected for by controlling for assets. Appendix II discusses some of these characteristics with the fine resolution weather data that was obtained from ECWMF. In addition, as stated in the methodology, there are numerous other factors that affect income, including, but not limited to, changes in market prices, new investments, operations outside of the target region, and risk management techniques already implemented. Furthermore, the assumption of a linear relationship between each of these weather values and income may not be accurate. Finally, non-linear regression and assumption of non-normal distribution may be an improvement for further studies. The distribution of the meteorological variables can be found in Appendix II.

The correlation values were lower than expected, but again, given the number of potential sources of error, these numbers should be viewed very cautiously. Given more input data this analysis could be very useful in estimating the weather exposure of the renewable energy sector. A smaller time interval would improve this analysis greatly there is still a time horizon for when many of these companies started appearing. The companies surveyed by Pérez-Gonzáles and Yun have existed for a lot longer than the companies used in this analysis.

**Table 8. Pearson Correlation Coefficient between volatility values**

| Variables | Income Volatility | Cloud Weather Induced volatility | Wind Weather Induced volatility |
|---|---|---|---|
| **Income Volatility** | 1 | | |
| **Cloud Weather Induced volatility (Beta*Std Dev)** | 0.183 | 1 | |
| **Wind Weather Induced volatility (Beta*Std Dev)** | 0.057 | 0.771 | 1 |
| **Precip Weather Induced volatility (Beta*Std Dev)** | -0.017 | 0.228 | 0.624 |

## 5.2 Interview Results

As expected there was a wide range of responses from interviewees touching on many different aspects of weather risk, weather derivatives, risk management, and renewable energy. Not all of the interviewees touch on all of the themes, but a large percentage of participants provided responses for each area. Their responses are analyzed through the framework described in Chapter 2. This section is broken into 6 parts for each of the coding themes used in the analysis: investment, derivative contracts, derivative market, general risk management, stories and projections, and other.

### 5.2.1 Investment

The theme of investment covered many areas, including the concerns of investors and operators, debt, discounting, and demographics. The questions "Is weather variability a concern?" or "Is weather variability a concern when considering investments in renewable energy?" were answered by six interviewees and showed division among respondents. Interviewees involved in selling renewable power and in developing it, expressed little concern over revenue. The CEO at a renewable energy company (pers. comm. 2014) stated that they expected variability so they were not concerned. They also said they buy power on the spot market when necessary. The president of a renewable energy development company (pers. comm. 2014) mentioned that loss of productivity was a secondary concern that needed to be quantified and managed, but ranked severe events that physically threaten the project as a higher concern. To support this, the developer cited the fact that the parent of major re-insurance company owned by Warren Buffet, experts at risk management who are also well aware of the weather and climate change, was significantly increasing its investment in wind to the tune of about US$6 billion (President of a renewable energy development company pers. comm. 2014). In these discussions, the CEO at a renewable energy company (pers. comm. 2014) was referring more to the operational stage than the investment one, but the President of a renewable energy development company (pers. comm. 2014) was referring to both. A low concern about this type of weather risk means that the tools to manage this risk, like weather derivatives, unlikely to be considered for use.

Other respondents gave a very different opinion. The director of an investment organization (pers. comm. 2014 ) gave a definitive yes to this concern, but only to the development phase of the project, i.e. finding optimal sites for projects. Here, lowering the perceived risk of weather variability may make more projects ,or more sites, favorable to investment. The analyst at an energy trading company (pers. comm. 2014), thought that this was a risk that would illicit more concern in the future. They said that, currently, subsidies were the primary factor influencing investment, and that risk management of renewables in the way described would only become a concern once renewables were able to stand on their own. In the context of the framework, the energy policy has modified the risk-return profile of the project so much that is became the dominate factor in investment. The weather derivative team lead at an energy company (pers. comm. 2014), a provider of weather derivative products, said that there was not enough concern about weather variability among investors or operators. They did not elaborate on why this was, but this agrees with the comments from the seller, the energy trading analyst, and the developer.

The originator at reinsurance company (pers. comm. 2014), also a provider of weather derivatives, said that this was a concern because it was one of the risks that operators cannot control themselves. That only weather derivatives would be able to provide cover for this previously unmanageable risk (Originator at reinsurance company pers. comm. 2014; Thornes, 2003). They also mentioned that is this a relatively new worry, previously investment in projects was done mainly by vertically integrated utilities and the conditions under which they developed were very good. Vertically integrated utilities have a lot of diversification in their portfolio (Partner at insurance broker pers. comm. 2014), renewable energy would increase this diversification, and possibly provide additional natural hedges, making them more attractive for investment. This is no longer the case (see below)(Originator at a reinsurance company pers. comm. 2014). Smaller firms are not as able to diversify as larger firms (EIU 2011). In terms of ranking risk, the reinsurance originator, put this risk in the same category of catastrophic weather risk and political risk.

The general sentiment seems to be that risk is there, and there is some concern, even if, like the seller, they feel it is well managed. The variation seems to be whether there is 'enough' concern or not. Some of this may have come from the way the question was asked, with some interpreting the question as applying solely to the concern of investors and other as applying to the concern of operators. Another may be their perspectives, however some, like the weather derivative lead at the energy company, did acknowledge their interests in this area however, saying "…as a professional in the weather risk market, of course I want as many companies as possible to use these services, not only because I want to make a living, but also because I think it makes sense…" (Weather derivative team lead at an energy company pers. comm. 2014).

Providers of weather derivatives who responded also said the concern on the part of the financiers was mitigated somewhat by the buffer or discount banks and investors apply to new renewable projects. Interviewees explained that when calculating payback, investors estimate much lower output than the ideal case. Modelers, like the consultant at the wind modeling company (pers. comm. 2014), who build models of average energy production for a project based on 20+ years of data, and then calculate the amount of power that would be produced in some percentage of cases, this individual mentioned 90%. This is then sent to investors who feed it into their financial models (Consultant at a wind modeling company pers. comm. 2014). Other interviewees involved in the weather derivatives market and investment all gave production probability figures of between 80% and 95%. The advisor at an environmental investment firm (pers. comm. 2014), explained that a 'P90' estimation of wind power output means that they are assuming the output from a plant that will occur in 90% of cases. This means that there can be a sizable variation in wind from the ideal case and the operators will still be able to service their debt. Only fluctuations outside this range are of serious concern. Which is possible, the weather derivative team lead at an energy company (pers. comm. 2014) noted that it is possible to have a 70-75% wind year. The advisor at an environmental investment firm (pers. comm. 2014) went on to explain that banks can also add a margin to an installations predicted earnings. The example given was 1.4 times the debt payment, this means the earning can fall by up to 28.5% and operators will still be able to cover their debt. However, this lowers the amount that can be borrowed for projects. This is a way in which investors can consciously alter their perceived risk and return. By lowering the return expectations, they are also lowering the risk that their expectations won't be met.

As mentioned earlier, the originator at a reinsurance company (pers. comm. 2014) explained that a shift in equity holders occurred from vertically integrated utilities to sovereign fund, pension funds, and private equity holders. Wüstenhagen and Menichetti (2012) said that all investors cannot be treated the same, and will have different expectations and investment patterns based on their position and investment history. This shift in particular means that the focus is now on smaller, constant returns (Originator at a reinsurance company pers. comm. 2014). They noted that weather derivatives helped achieve these 'smaller, constant returns' by effectively putting a floor on the production revenue. It also changes the risk profile of the project for investors and banks, affecting the premiums on the project (Originator at a reinsurance company pers. comm. 2014). Echoing Pérez-González and Yun (2013), the originator at a reinsurance company (pers. comm. 2014)said that this shift in risk profile means that a project may have access to more debt or better financial conditions. This is advantageous as the reinsurance originator also said "…because debt is not as freely available, conditions are more stringent. And as we've seen, the governments are starting to back down in their enthusiasm for renewable energy and the level of support, financial support, that they are providing" (Originator at a reinsurance company pers. comm. 2014). Again, echoing the energy trading analyst that policy has a dominating role in the investment process (Analyst at an energy trading company pers. comm. 2014).

The weather derivative lead also provided the interesting example of when the financing of a project was directly linked to weather derivatives (Weather derivative team lead at an energy company pers. comm. 2014). They said they knew that a handful of these deals had been done in relation to renewable energy by banks in the early 2000s. They explained the general terms of such a deal,

> …they sold it as a package: financing including a wind hedge. … the wind farm operator ultimately owned a put option on a wind index and at the same time sold a call option with a higher strike, so if the wind

> goes crazy, above, say 110%, they made a payment ultimately in our direction, if it was below, I don't know, say 95% or so, we made a payment in the other direction (Weather derivative team lead at an energy company pers. comm. 2014)

While these exact details don't appear to be as common now, they do demonstrate that there was enough interest in this risk for some banks to include it as a condition for financing.

### 5.2.2 Derivative contracts

The exact details of derivative contracts, other than those available on the CME Group exchange, are considered sensitive information. Contracts are highly customized (Weather derivative team lead and an energy company; Originator at a reinsurance company; Partner at an insurance broker; CEO of met. data and consultancy pers. comm. 2014). However, interviewees were able to provide general information about OTC derivative contracts including the construction of the contracts, the data required for their construction, the length of the contracts, typical counter parties, and pricing.

When talking about writing contracts, customization was a recurring theme. The partner at an insurance broker (pers. comm. 2014) said that every deal they had transacted was specific to that situation. The providers of weather derivatives explain that they start by creating a model relating power generation to the weather based on historical measurements, similar to the models used by investors in the previous section (Weather derivative team lead at an energy company pers. comm. 2014). They then tweak this index so it matches with actual wind measurements or power readings at the site. If all parties are happy with the index they then use that to structure a weather derivative product, including the type of contract (e.g. put, call, etc), the tick, and the strike (e.g. 90% of the long term average) (Weather derivative team lead at an energy company pers. comm. 2014). Because of the level of customization, these contracts can get very complex. The CEO of a met. data and consultancy (pers. comm. 2014) believes that this complexity is a big benefit of OTC contracts. It allows the products to address the specific concerns and needs of the investor or operators, reducing the perceived risk of the project.

Interviewees, in line with the literature (Thornes 2003; Zheng 2000), placed significant emphasis on data quality because of the importance of accurate meteorological data in constructing the index on which the weather derivative is based, settling contracts, and finding a low-risk site right from the start. The advisor at an environmental investment firm (pers. comm. 2014) said that prior to investing in new wind installations investors want 10+ years of historical data, combined with a year of data from a wind mast on site. Again, allowing investors to quantify the basic risk and return of the project All interviewees who talked on this mentioned the need for the data to come from a trustworthy third-party source, like a national met office, or third party data provider. One surprising fact from this discussion was that the use of model data is fairly common, contrary to what some previous papers stated about the need for secure weather stations to settle contracts (Müller and Grandi 2000; Randalls 2006). The weather derivative team lead at an energy company (pers. comm. 2014) talked the most on this saying that previous models were very coarse, on a 2.5° longitude by 2.5° latitude grid, which was not very useful in settling contracts. Modern models providing reanalysis data are much finer, ERA-INTERIM's resolution is on a 0.75° by 0.75° (ECMWF 2014) which is fine enough for settlement.

Once the index is created, the weather derivative can be constructed. Based on talks from the AMS Conference, which included information on how CME trading works, I expected contracts to last a season, or no more than a year, however this is not the case. While the partner at an insurance broker (pers. comm. 2014) reinforced the idea that contracts are 'one-off' and not automatically renewable, all weather derivative providers said that multi-year contracts weren't out of the question. The use of model data, as well as a few years of data from the operational phase of the plant were given reasons for allowing a longer contract. Two providers gave figures of up to three years with five being a stretch for the longer term contracts (Weather derivative team lead at an energy company; Originator at reinsurance company pers. comm.

2014). The insurance originator (pers. comm. 2014) explained that clients ask for long term contracts up to 10 years. Their clients want to be covered for the same length as their commitments to their financiers. Providers of derivative products aren't comfortable with contracts that long yet, but they are usually willing to renew the product at the end of the term, under updated terms based on new data obtained in the intervening years (Originator at a reinsurance company pers. comm. 2014). This means that derivatives cannot be guaranteed to provide risk management for the lifetime of the project. There is a risk that when the time comes up for renewal the terms will no longer be favorable.

This unexpected response to the questions on the length of contracts, led to climate change being brought up in the discussions by the researcher. The reasoning was that climate change would add risk and uncertainty to longer term investments. In addition, the longer a contract is, the greater the risk that trends in climate change may undermine the underlying index on which the contract is based. The general response was that they acknowledge that it may have an impact, and they do incorporate those trends and projections into their models. However, the originator at a reinsurance company (pers. comm. 2014) reflected the general sentiment in this area by saying that it is not a pivotal concern at this point. The president of a renewable energy development company (pers. comm. 2014), said that this was a question they didn't have a good answer for, but expressed their opinion that it was an area that needed more attention. While climate change may be behind the motivation to expand renewable energy, based on the somewhat tepid responses here, its effect on local weather patterns don't appear to significantly influence investment decisions.

The price of contracts was not a major topic of discussion, however, a couple of interviewees did give comments on the matter. The weather derivative team lead at an energy company (pers. comm. 2014) said that many of the people selling these products believe that the market is smaller than it actually is and so some parties have 'certain price expectations'. The partner at an insurance broker (pers. comm. 2014) corroborated this sentiment with a story of how a major corporation brought a 'new' weather product on the market, which their company had been offering for several years prior. Given that "these products are kept close to the chest" (Partner at an insurance broker pers. comm. 2014), they did not seem imply copying or stealing from the above story, rather outdated knowledge on the part of that corporation. When talking about price specifically, they mentioned that they compare their weather products to existing, readily available, products on the energy market. Price is an important aspect in determining if weather derivatives can improve investment. If the price is too high, the cost to operators may outweigh the benefits of having the contract by taking too much out of the revenues.

Finally, onto the topic of counter parties, or the people or organization on the other side of a contract. For traditional energy future contracts, energy suppliers are the counter parties (Analyst at an energy trading company pers. comm. 2014), but that is not the case with weather derivatives. If major insurers/re-insurers are offering weather derivatives, then they are the counter parties for their clients. They can do this because, the originator at a reinsurance company (pers. comm. 2014) explains, "…weather derivatives hold no correlation to all other risks the company has on its books. It doesn't hold relation with financial markets, …political risks, and catastrophic weather markets." Other counter parties include capital providers (Partner at an insurance broker pers. comm. 2014), investment banks are starting to leave this area, but, as mentioned before, others like hedge funds are starting to enter (Originator at a reinsurance company pers. comm. 2014). Some large energy corporations have their own trading departments for moving risk around different areas of the company (Weather derivative team lead at an energy company pers. comm. 2014). In this case the corporation is its own counter party, although some of that pooled risk is then transferred to another entity (Weather derivative team lead at an energy company pers. comm. 2014).



### 5.2.3 Derivative market

The derivatives market is broken into two parts, the exchange or CME side, and the OTC side. Determining the size of the whole market is difficult, but interviewees were able to provide what information they had on the size of the market and how it compares to other markets, the evolution and current state of the market, how the market is specifically for products that can be used by renewables, liquidity and the secondary market, and CME Group.

All interviewees who provided responses on the weather derivatives market work for member companies of WRMA. There are about 50 members in WRMA, and around half of those are either users of weather derivatives or active providers (Weather derivative team lead at an energy company pers. comm. 2014). One interviewee estimated from the WRMA survey that about $15 billion in risk was transferred through in 2012, though not exclusively renewable contracts. The originator at a reinsurance company (pers. comm. 2014) said that 90-95% of utilities hedge their exposure to volumetric risk and that renewable energy companies are starting to look more closely at the products than before. Even determining the size of the market on the exchange is difficult, a respondent questioned whether weather derivative contracts should be valued in the same way as traditional derivative contracts, and what effect that would have on the calculated market size. Other respondents were not able to provide much information in this area, an energy trading company was not aware of anyone who used weather derivatives, at least in the renewable sector.

Many energy companies use weather derivatives to hedge demand because there aren't many other options (Originator at a reinsurance company pers. comm. 2014). They very good at hedging against fluctuations in prices of electricity and gas, but volume is much harder to deal with. Due to the harsher financial environment mentioned in the investment section, and the advancements in technology, i.e. models, renewable energy companies are starting to look more closely at weather derivatives as well (Originator at a reinsurance company pers. comm. 2014). There is also some speculation occurring (Weather derivative team lead at an energy company pers. comm. 2014) , such as what will next winter be like in terms of temperature.

Currently, traded numbers in the market are down significantly from a few years ago (Weather derivative team lead at an energy company pers. comm. 2014). This has to do with financial players reevaluating their core business after the financial crisis and exiting the market. The OTC market, "the real hedging market" has be steadily increasing, and a lot of the volume lost as come from the secondary market, e.g. CME (Weather derivative team lead at an energy company pers. comm. 2014). This is the opposite of the findings of Randalls, who in 2006 who found the reverse situation in Europe. Even with the recent reduction in the number of players in the market, liquidity as not been a problem. The weather derivative lead recalled, "…whenever we've wanted to place a deal we've placed it. There might have been a situation where we didn't like the pricing levels in general, but that wasn't down to there only being one or two sellers" (Weather derivative team lead at an energy company pers. comm. 2014). The reinsurance originator also mentioned that this downturn is starting to end, "We've seen stiffer competition, we've seen new players, and non-traditional players in this aspect…[in reference to the hedge funds mentioned in the previous section]" (Originator at a reinsurance company pers. comm. 2014).

Looking towards the future, active market participants see the market growing steadily into the future for a variety of reasons including a maturation of the market, more stringent financing conditions, and more renewable energy on the grid. The CEO of a met. data and consultancy company (pers. comm. 2014) said they felt the market was still in its early days. Respondents said that in terms of activity, the US is by far the most active, with the UK, Germany, and France being active as well. North American, Europe, and Australia are the primary regions weather derivatives are traded. However, some of the stories given by respondents show that countries in Africa and South America participate as well. This means that companies and organizations over a wide geographic area, in theory, have access to these products. It should be noted here, that most of the conversation surrounding this topic was directed towards the weather derivative market as a whole, not specifically the segment that caters to renewable energy companies. In addition, while transactions have been done in these areas, some countries, like Mexico, do not allow for these products to be sold as financial products, they would be regulated under and treated as insurance (Fadhl et al. 2008).

When the discussion did focus more on the segment that could apply to renewable energy companies the responses were much less promising than expected after initially reviewing the literature. The weather derivative team lead at an energy company (pers. comm. 2014) was able to confirm a handful of renewable energy supply hedging trades took place that involved wind and hydro power. The originator at a reinsurance company (pers. comm. 2014) said that hydro was one sector they had worked with, and that it was probably a better area to look into than wind, which had very few. They reiterated that in the weather derivative market the majority of contracts are for temperature. The CEO of a met. data and consultancy company (pers. comm. 2014), also wasn't able to provide much information on wind, due in part to the fact that those contracts require some modeling, which is outside of their business area. However, they were able to say that rainfall contracts have been conducted in South America, the United States, and Australia, and that snow contracts had been conducted in the US. They also said that rainfall deals they were aware of didn't affect the funding potential of new installations, rather they were used for existing assets. While the number of hydro deals is relatively small, the payout on them is fairly large (CEO of a met. data and consultancy company pers. comm. 2014). The stories section of this chapter provides a recent example of a hydro deal worth half a billion dollars. The insurance originator (pers. comm. 2014) also sees the potential for a combination of new wind/renewable products and the more traditional temperature derivatives in the future to hedge all weather-related volume changes.

The CME Group, while a US based company, covers both the US and Europe. Active trading cities in Europe include London, Paris, Amsterdam, and Essen (Originator at a reinsurance company pers. comm. 2014). However, the originator at a reinsurance company (pers. comm. 2014) felt that the significance of CME contracts is lower than what it used to be. The weather derivative team lead at an energy company (pers. comm. 2014) estimated that the over the counter European trades were 5 or 6 times the entire European CME market. Other than the presentations at the AMS Conference, no one from CME Group was available to talk on their exchange or role in Europe. Regardless, CME Group's current role in the potential renewable energy side of the market is small as they only offer one product, rainfall, that could be used to hedge against changes in renewable energy supply.

### 5.2.4 General Risk Management

Discussions among individuals not directly involved in the weather derivative markets, distributors, developers, and investors, often strayed into more general risk management techniques. These techniques touch on both the investment and operational phases. They are interesting to add into the discussion because weather derivatives are not, or would not, be used in isolation, but part of a more comprehensive risk management portfolio that deal with risks beyond the weather. Some of the techniques presented may reduce or eliminate the need for weather derivatives in some cases. Others may be able to deal with other risks at the same time. The analyst at an energy trading company (pers. comm. 2014) pointed out the political risk related to subsidies, 'market inefficiencies and distortions', and catastrophic events not related to the company that can all impact revenue. They also affect investment decisions.

Diversification is the most often used method to manage risk at the company and investor level. Diversification is attractive because it's free, or at a minimum doesn't require purchasing products or services, or entering into a contract with another company. The weather derivative team lead at an energy company (pers. comm. 2014) explained how technological diversification over a small geographic area can provide natural hedges. Different technologies have different weather risks associated with them, for example, a stormy day may be good for wind, but bad for solar. The partner at an insurance broker (pers. comm. 2014) talked about vertically integrated utilities, which have retail positions as well as a range of generation types. The advisor at an environmental investment firm (pers. comm. 2014) reiterated that investor portfolios will probably be diversified in other projects across different geographical regions, as this protects them against not only variations in weather, but also against political risk, or changes in government policy. When it comes to investing, the effects of diversification in the expanded risk-reduction framework can be significant. The weather derivative team lead at an energy company (pers. comm. 2014) provided a story of a company active in Northern Europe, that was looking to diversify their portfolio by investing in Southern Europe rather than purchasing a hedge.

The advisor at an environmental investment firm (pers. comm. 2014) said that some private equity funds may not hedge at the equity level, because they look for high-risk, high-return investments. Utilities may look for lower yielding and lower risk projects, which will be diversified across their portfolio.

At the operational stage the seller and developer interviewed seemed relatively unconcerned with this risk. The CEO at a renewable energy company (pers. comm. 2014) said that they purchased power on the spot market to hedge variability in production. This may be linked more with concern over not being able to deliver rather than financial risk. The president of a renewable energy development company (pers. comm. 2014) said that they look to their insurance companies and their meteorologists to anticipate and cover the risk of weather variation and extreme weather. Although this does not necessarily relate to low-risk, high-probability weather risk, the advisor at an environmental investment firm (pers. comm. 2014) mentioned that wind manufacturers also provide some level of guarantee on how much wind turbines will be operational, usually 97%. In addition, the analyst at an energy trading company (pers. comm. 2014) said that residential customers in many countries have fixed contracts, which do not require hedging for price. They don't mention if this affects volume. The consultant at a wind modeling company (pers. comm. 2014) echoed these responses, stating that maintenance plans and forecasts are used to anticipate and deal with risk. My impression from the seller of renewable power and the renewable energy developer was that they felt these risk management techniques were adequate.

An interesting point that came up about risk management that wasn't uncovered during the literature review was that companies do not want to transfer all of their risk. The weather derivative team lead at an energy company (pers. comm. 2014) and the analyst at an energy trading company (pers. comm. 2014) both talked about how companies retain some risk in their portfolio. When referring to transferring bundled risk, the weather derivative team lead at an energy company (pers. comm. 2014) said, "it's fair to say we always put on hedges, at the same time we always try to retain a certain portion in our book, just to further diversify our portfolio…sometimes we do a 100% back to back trade, but that's rare." The analyst at an energy trading company (pers. comm. 2014) explained that companies have a limited budget that can be spent on risk management, sometimes the cost prevents companies from offloading more risks. Usually, a dynamic risk management strategy is used with a large percentage of 'certain' contracts, and a smaller percentage of 'floating' contracts (Analyst at an energy trading company pers. comm. 2014). Floating contracts give the potential for savings or losses from fluctuations in volume or the market, something I initially thought companies wanted to avoid.

### 5.2.5 Stories and projections

Interviewees also provided an incredible range of stories and anecdotal evidence, some surprising insights as to how weather derivatives are being used, their relation to renewable energy, where they may be going in the future, as well as a dissenting opinion. Some provide specific examples of how weather risk management is currently being used by renewable energy companies, which was surprisingly rare.

The most cited example of a weather derivative used to hedge variability in renewable energy is a contract with utilities in Uruguay valued at approximately $0.5 billion (Weather derivative team lead at an energy company; originator at reinsurance company; CEO of met. data and consultancy company pers. comm. 2014). It was a rainfall contract linked to oil prices. Unlike most OTC contracts, this was a very public deal that was facilitated with the help of the World Bank. The weather derivative team lead at an energy company (pers. comm. 2014) explained that in this country, if there is less rainfall, then hydroelectricity cannot be produced cheaply, and oil needs to be purchased. So, the contract will payout if rainfall goes below a certain about and the payout is linked to the current market price of oil, with a cap on the maximum payout. The utilities paid approximately 10% of the maximum in premium upfront to the counter parties, a major re-insurer and an investment company. They also noted that the deal was very large for the weather derivative market, but small compared to other derivative markets. The index-based insurance deal in Malawi, which was mentioned in the literature review, also came up, as did another deal in Ethiopia. Again, this shows that this concern and these deals are not necessarily restricted to the US, Europe, and Australia. The weather derivative team lead at an energy company (pers. comm. 2014) did acknowledge that is it probably more difficult to make these deals after the data availability in these countries was questioned, but mentioned that having a neutral body like the World Bank facilitate the deal helped. As far as can be ascertained, this deal did not directly affect any investment in renewable energy, but it is still a good example of a renewable energy weather hedge.

Most interviewees were also asked about why they believed renewable energy companies were not using weather derivatives. The responses were extremely interesting, although not always directly related to renewable energy. The weather derivative team lead at an energy company (pers. comm. 2014) believed it was only a matter of time, that as the market matures more companies will be inclined to look towards these products for protection on the supply side as well as demand. However, they did acknowledge that some of the indexes that go into making products for the supply side are more complex. The originator at a reinsurance company (pers. comm. 2014) thinks that renewable energy providers will start using them, but there is a lack of knowledge as well as institutional inertia for the risk managers at these companies who focus more on traditional insurance risk. This fits the expanded risk-return model nicely, actors will favor investments that they've made before. The partner at an insurance broker (pers. comm. 2014) said he expected a range of answers from energy companies to this question, but believed price was definitely a factor. The CEO of a met. data and consultancy company (pers. comm.

2014) explained that large diversified energy companies don't have much incentive to purchase contracts because they most likely have natural hedges, and that the real economic value of these products comes from organizations where weather risk is, figuratively, a matter of life and death.

Outside of the WRMA community the responses had a slightly different tone. The CEO at a renewable energy company (pers. comm. 2014) had not heard of these products at all, which corroborates what the insurance broker (Originator at a reinsurance company pers. comm. 2014) said. The president of a renewable energy development company (pers. comm. 2014) was extremely skeptical of, and even hostile to, derivatives, describing a predatory side of derivatives. They recognize that derivative markets can be used to manage risk, and acknowledged there might be potential, but questioned the real usefulness and fairness of financial markets. Using, "if you only have a hammer, then all your problems look like nails" to describe the use of derivatives in solving so many problems (President of a renewable energy development company pers. comm. 2014). This echoes the skepticism and concern many news articles I came across had towards financial derivatives in general, especially after the recent financial crisis (Denning 2013; Valladares 2014). However, the demographics of the interviewees don't allow any wider statements on the general opinion of these actor groups to be made.

So, operators, investors, and sellers of renewable energy are not using weather derivatives regularly for the variety of reasons stated above. Yet at times during the interview period, participants gave contradictory information. Wind and other products are definitely being sold, but renewable energy companies rarely buy them. A quote from the partner at an insurance broker, "Not necessarily the wind owner, the owner of the wind farms, but could be another organization that is exposed to the amount of wind that is available or going into the market place at a particular time." (Partner at an insurance broker pers. comm. 2014). So who else is interested in these products, who else may wish to use them in the future, and what might that mean for renewable energy? In order to understand that, an understanding of renewable energy's effects on the rest of the market is necessary.

The effects of renewable energy on power markets was brought up in 5 interviews, but was only prompted by the interviewer in three of them. The consultant at a wind modeling company (pers. comm. 2014) explained that the grid needs supply and demand to be balanced. They need forecasts for power production in order to keep that balance. When lots of renewable power floods the market at once, or suddenly disappears, both a function of weather variability, the strange things happen on the spot market for electricity. When renewable stations stop producing, the price spikes, which is expected (Weather derivative team lead at an energy company; Partner at insurance broker; Analyst at energy trading company pers. comm. 2014). However, when energy floods the market the spot price can go negative, meaning that operators need to pay in order to keep producing (Weather derivative team lead at an energy company; Partner at insurance broker; Analyst at energy trading company pers. comm. 2014). The weather derivative team lead at an energy company (pers. comm. 2014) believed that is was a phenomenon that had not really been addressed yet with weather derivatives. The analyst at an energy trading company (pers. comm. 2014) explained that when this happens, or is about to happen, some power plants get kicked offline to reduce the supply of energy on the grid. The exact hierarchy depends on the country, but, as an example, in Germany, renewables get priority access to the grid, nuclear power is difficult to adjust quickly and so is allowed to keep producing, leaving a mix of conventional power plants to round out the bottom (Analyst at an energy trading company pers. comm. 2014). The originator at a reinsurance company (pers. comm. 2014) called the possibility of this event occurring the curtailment risk, and gave an example of a coal plant that only operated for a few hours out of the year because of the output of plants with a higher priority. Presumably that is a goal of policies that are designed to increase the share of renewable power on the grid. However, the analyst at an energy trading company (pers. comm. 2014) thinks these subsidies are unfair because it doesn't just benefit renewables, it also directly hurts traditional operators.

The traditional operators are the potential alternative users of these weather derivative contracts, giving them the ability to hedge against the this curtailment risk (Originator at a reinsurance company pers. comm. 2014).[8] This may provide additional counter parties to renewable operators, making weather derivatives more available and perhaps lowering the price, since they have opposing risks, and swaps are usually cheaper than other options. When the wind, for example, is not blowing traditional energy companies would pay renewable energy companies and vice versa. However, it's questionable whether this is of significant benefit because it was already mentioned that liquidity is not really a problem in the OTC market. At the very least there is some incentive on conventional operators to either invest in renewables to diversify, or to enter into these contracts in order to better manage their own risk.

### 5.2.6 Other

Interviewees also provided very helpful information not just in answering my research questions, but also in finding other sources of information and understanding some the culture of the weather derivative community. The originator at a reinsurance company (pers. comm. 2014) helped me to better understand the difference between weather derivatives and other risk management products like insurance. They explained that weather derivative products can be structured like insurance, the major difference being that with insurance your financial benefit cannot be greater than your loss, but that there really is no line. They also explained that most of the computer models they used are in good agreement with each other when it comes to making contracts, which influenced my choice in dataset for the quantitative analysis. The partner at an insurance broker (pers. comm. 2014) warned that there is a lot of information providers of derivatives and users were likely not going to release or talk about. They also, along with the weather derivative team lead at an energy company (pers. comm. 2014), pointed out exactly how



[8] The fluctuations mentioned above did not cause blackouts. The German government passed legislation to help prevent blackouts due to these fluctuations. Part of this involves paying large consumers to stop operating during times of crisis from fees levied. This may be another potential use for weather derivatives, both utilities that would need to pay per MWh for these facilities to shutdown, and any additional lost income from the factories that went dark. (Eckert 2012)

small this field was, and that it may be possible for someone to deduce who the interviewees are. So in addition to anonymizing potentially identifiable information in stories and comments, interviewees were also given an opportunity to review a draft of this thesis and request that potentially sensitive information be altered.

## 5.3 Annual Report Results

Due to the lack of response from renewable energy companies, an alternative source for information on risk management in energy companies was sought. The annual reports of six energy companies operating in the UK were reviewed for information on both how they view non-catastrophic weather risk and what, if any, hedging strategies they utilize to manage that risk. These companies were chosen because they all had renewable energy as part of their generating portfolio and include 4 of the "Big Six" in the UK. Not all of the target companies in the UK were public, some of them were wholly owned subsidiaries of companies in other countries. In those cases the annual reports reflected the views and policies of the parent company, not just the UK division. These are large companies, who do not exclusively operate renewable plants.

All of the annual reports reviewed mentioned weather was a concern, however the apparent level of concern and amount they include the weather in their discussion varied considerably. ScottishPower Renewables' parent Iberdrola (2014) mentioned weather was a business risk, but did not specifically elaborate on how it impacted their business. EDF (2014) on the other hand, had multiple sections devoted to weather risks, both catastrophic and non-catastrophic, as well as the effects of weather on their bottom line, positive and negative. Specifically, they mentioned how part of the increases for the previous year could be attributed to a colder than average winter in France, and that a return to 'normal' weather conditions could hurt their revenue in the coming year (EDF 2014). Infinis (2014) pointed out some weather impacts on their business that were extremely surprising. For instance, they mentioned how "the wet weather in the year helped to ensure the integrity of the caps over landfills and protect from gas leakage" in a year with a declining gas yields (infinis 2014). All companies at least acknowledged that the weather has an impact on their business, and most detail not only how their business areas are vulnerable to changes in weather, but also use it to explain fluctuations in their performance.

The impact of weather on the supply of renewable energy in these reports receive somewhat less attention. Most of the non-catastrophic weather discussions focused on how temperature impacted gas and electricity demand. E.ON, RWE, Southern Electric, and infinis all talk in some way about weather affects the supply of energy, or how wind affects their business, including indirect effects (E.ON 2014; RWE 2014; SSE plc 2014; inifinis 2014). RWE stated, referencing the German market, "The problem is that under different weather conditions and at other times of the day, huge amounts of green energy flood the grid and drive down prices on the exchange" (RWE 2014). However, most statements are more specific to the company, like this excerpt from infinis, "The weather can adversely affect each of our generating activities. Lower wind speeds than anticipated will result in less electricity generation. This is an increased risk for the Group as the installed capacity of wind increases. Dry weather can adversely impact LFG [landfill gas] and hydro generation" (infinis 2014).

When it comes to managing these risks most companies are much less detailed. Iberdrola and EDF among others mention that insurance covers them for certain types of weather risk (Iberdrola, S.A. 2014; EDF 2014). Iberdrola (2014) also mentions that some operational risk cannot be covered by insurance, presumably non-catastrophic weather risk is included in this category. E.ON explains how they expect weather to impact their business in the future, for example, "Mild weather in the first quarter could lead to a decline in European gas prices in 2014" (E.ON 2014). All companies that have a detailed discussion on weather risks have similar speculation. Infinis also very generally states how they intend to deal with these risks through non-financial means, "We monitor both weather and atmospheric conditions as these affect our LFG, wind and hydro operations. We optimize the management of our engine and turbine fleet and gas fields according" (inifinis 2014).

No company specifically mentions weather derivatives as a risk management tool, let alone weather derivatives specific for managing renewable energy production. However, all companies utilize derivatives products as a hedging tool, most commonly for currency, interest rate, and other financial risks. Sections of the reports on financial hedging leave open the possibility for weather derivative use. For instance, many financial statements have an "Other" category for derivative assets. In addition, it is possible weather derivative contracts may be included in commodity or cash flow hedges, but this is just speculation and seems doubtful as these titles traditionally refer to other types of contracts. Southern Electric (SSE plc 2014) does state that they use derivatives to manage both price and volume risk. This has a much higher probability of referring to weather derivatives. Although, this likely refers to temperature derivatives like (HDD or CDD), rather than derivatives that would be used to hedge renewable energy supply volume risk. There is also a chance, that since these products are often issued by reinsurance companies they might be lumped under insurance rather than traditional derivatives.

This review does not shed significantly more light on the use of weather derivatives in renewable energy. Most likely because, as evidenced from the interviews, they are not being used to hedge the volume risk associated with renewables, and also, like the interviews, some information is proprietary and not available in the reports. However, I had expected to see some indication of temperature derivative use in these reports, given the assumption that 90-95% of energy companies use them (Originator at a reinsurance company pers. comm. 2014). Perhaps they are not the best source for specific company risk management strategy. This review does provide some useful insights into how companies view risk. Many of these reports were much more detailed than expected in explaining their exposure to weather. Sometimes attributing changes in revenue to the weather, and listing out non-financial ways of managing that risk. Companies are thinking about weather risk, and a few in this limited sample even list ways they try to manage or adapt to it rather than just take the acceptance route of risk management.

# 6. Discussion

The previous chapter described the data collected, and related that information to the framework described in the literature review. This chapter attempts to summarize and synthesize that information into concise and coherent responses to the research questions. It also explains the limitations of this research, and proposes areas of future research.

## 6.1 Weather Variability

The inconclusive results of the quantitative analysis don't provide much basis for making statements about the exposure of European alternative energy firms to weather risk. Fortunately, the annual reports provided very detailed information on the perceived impacts of weather variability on energy companies, and interviews complimented this information nicely. Low-risk, high probability weather events affect this industry and renewable power in the way outlined by the literature, although the perceived risk is not as great as expected. The renewable energy sources that are dependent on the weather for generation, including wind, solar and hydro, are vulnerable to variability in output. One interviewee even noted that bio-fuels dependent on agriculture are also exposed to this risk, but that is beyond the scope of this research. The most of the annual reports use variations in weather conditions to explain changes in their revenue.

Major fluctuations, and long term deviations from historical averages have two potential implications for renewable energy companies in regards to investment. First, frequent fluctuations in weather means that companies need to take on less debt, and have more cash on hand to ensure that they can make their existing debt obligations. Ultimately this means that renewable energy providers have less capital available to reinvest in the company. Second, below expected revenue over an extended period of time raises the risk that companies will default on their obligations to their financiers. This is a risk that financiers take into account when deciding whether to provide loans or funding to a new project. However, this perceived risk is mitigated by taking a large discount out of the expected revenues of new installations based on detailed models of wind speed and power production specific to that site. Long term trends on weather conditions may also be affected by climate change. While it is a concern, it is not yet a significant one among any of the interviewees.

There is a wide range in risk management techniques that businesses use to reduce this vulnerability. The first, diversification, means that companies or investors hold assets with an array of technology and geographical variation. This increases the potential for natural hedges. Renewable energy companies may build over a wide geographic range to decrease the impacts of weather in a particular area. Other energy companies may find investments in renewable stations beneficial for their technological diversification potential. These actions minimize the impact of weather variability on the company as a whole, which appears to be level at which hedging decisions are made, rather than individual sites.

Other methods used to minimize these risks include forecasting production, maintenance contracts, long term power purchase agreements, using the spot market, and looking towards insurance. While none of these seems to directly correct the risk in question, both the seller of renewable power and the wind developer interviewed believe that these measures are adequate. However, providers of weather derivative products believed there should be more concern. Revenue is a function of both price and volume, even if renewable installations receive a set rate for their power using some of the methods above, either through feed-in tariffs or long term contracts, fluctuations in supply volume can still impact their revenue.

Finally, when a large percentage of the energy supply comes from renewables some of the variability in output translates into the power market. Stories of the spot price for electricity going negative, or spiking, and of other power plants shutting down due to an abundance of renewable energy illustrate that this risk can affect others in the energy industry as well.

## 6.2 Weather Derivatives and Investment

Weather derivatives have been used to manage volume variability due to weather in energy markets for 17 years now. While they have primarily been used to deal with demand side risk, they have also been used periodically to deal with supply side risk related to renewable energy. There has also been one case in which they have been required in order to obtain financing. That being said, their use in the renewable space is not common place, and so determination of systemic effects of derivative use on investment is difficult. A theoretical discussion is therefore necessary to see how weather derivatives could affect investment in renewable energy. This discussion brings in the framework of Wüstenhagen and Menichetti (2012), as well as firm finance mechanisms described by Pérez-Gonzáles and Yun (2013).

Weather derivatives have the potential to improve investment in renewable energy by changing the risk profile of a company or project, and by freeing up assets within a company for reinvestment. Pérez-Gonzáles and Yun (2013) described that by making the revenue stream more reliable, companies would need less cash, and could take on more debt to invest in new projects. From the external investor perspective, the use of weather derivatives among operators or requiring derivative-like clauses in contracts means that they can expect steady returns. This changes the perceived and actual risk profiles of the project.

These weather derivative products may set a floor on revenue and lower the weather risk associated with a project, but they are not free and they do not come without their own risks. For starters they do not eliminate risk, they merely transfer it to a third party, meaning that the holder of the contract still holds some risk in the form of counter party risk. Although if the trade is conducted with a large enough company, like a reinsurance company, then this risk is probably very low. If there is a set premium charged, that amount would need to come from revenues. If the contract is a swap there is a chance that the renewable plant would actually need to pay out some variable sum of money. This is not insurance, renewable energy providers could make a lot of money on these contracts, or they may not cover companies to their satisfaction. OTC contracts are customized to the buyers, but there is still give and take with the sellers. Weather derivatives are unlikely to bring windfall profits to renewable energy companies. Presumably investors and operators would perform their own risk-return analysis and determine if weather derivatives added enough value to the project to be worth the expense.

However, that determination does not appear to be happening as of yet. The next section will go into more detail on the current state of the weather derivatives market, but, based on the data gathered here, weather derivatives are not impacting investment on a large scale. As the weather derivative lead explained, they used help enhance finance deals in the early 2000s, but the actors who were involved appear to have left the weather derivatives market (Weather derivative team lead at an energy company pers. comm. 2014). Both the seller of renewable power and the renewable energy developer were relatively unconcerned with this risk, meaning either the variability does not impact their decisions on investments or they just accept the risk. Increased concern over this risk would probably increase the use of weather derivatives.

If the results from the statistical analysis are interpreted as a low relationship between renewable energy firms and weather events, then this may be an indication that firms are effectively managing some of this risk. However, again, the results from the quantitative analysis portion needs to be treated with skepticism.

Finally, weather derivatives and investment in diversification can only affect the companies that purchase or invest in them. It cannot change the actual amount of power being produced, or being placed on the grid. The other organizations that are affected by the variable supply that renewable plants generate would also need to invest in renewables or purchase weather derivatives to gain the same effect.



## 6.3 Use of Weather Derivatives

The use of weather derivatives among energy companies is widespread in managing demand side variability. However, the use of weather derivatives to manage the supply side variability in renewable energy is extremely rare. The direction this market is headed changes depending on who you ask. This lined up with the EIU (2011) report that found a majority of respondents said they were successful at mitigating risk, although that number was fewer than the ones who said they were successful in identifying risks. In addition, they said that insurance was the most common risk transfer mechanism, but found alternative risk transfer, like weather derivatives was growing. However, only 3% of executives in the EIU (2011) survey expected to make additional use of financial derivatives to hedge volume risk in the period from 2011 to 2013.

Interviewees in this research listed a multitude of reasons why weather derivatives aren't being used widely amongst renewable energy companies. On the provider side, lack of knowledge, cost, complexity of contracts like wind, immaturity, and institutional inertia were all given as reasons. The potential buyer side seemed to put this risk on a lower priority than others. They felt they had the risk managed using the spot market or insurance, or were suspicious of weather derivative products. The demographics of the interviewees don't allow wider statements about the feelings of renewable operators or the sellers of renewable power to be made. However, given the number of companies who use weather derivatives to hedge demand and growing concern expressed in the EIU report, more information on derivative use and weather risk management strategies in the annual reports was expected.

Looking towards the future, the use of weather derivative products in the renewable space will grow when two conditions are met. *The product needs to become mature and well understood in the eyes of renewable operators, eliminating any information gap about the nature of these products.* It might be very difficult to give actors not already in the market this knowledge given the confidential nature of these deals. Weather derivatives will also start to grow, *if and when the perceived risk, or need for these products, is great enough to justify the cost.* This could come about through a drop in price for these products, an increased exposure to weather variability, say though changes in government subsidies, or a relative increase in the risk itself, through the reduction of subsidies. Also, in relation to that last point, recall from the literature review that Randalls (2006) described actions by WRMA to try can get weather risk management included in the factors that determine a company's credit rating. If it is eventually included, then companies may be penalized in the form of a lower credit score for not managing this risk (Randalls 2006).

## 6.4 Problems and Limitations

This thesis attempts to ascertain the state of the weather derivatives market as it may apply to the renewable energy sector, as well as what effect these products may have on investment. From those that came before, as well as from advise from initial interviewees, it is clear that this is a difficult task. Problems were encountered and compromises needed to be made that ultimately limit the applicability of the findings of this thesis. Three areas of note come to mind, including initial assumptions of market size and data availability, selection of the annual reports, and the number and type of interviewees.

Based on several articles encountered during the literature review, including Alexandridis and Zapranis (2012) and Raizada (2013), and even some of the projections in the EIU (2011) report, I expected there to be more regular use of weather derivatives in the renewable energy sector to the point that they could be evaluated quantitatively. This was not the case, and the only data available was meteorological data, and the financial data of public companies. The average correlation between the variation in alternative energy company income and the various weather events can provide at least a rudimentary demonstration of the potential sensitivity of these companies to weather. However, these companies are affected by a significant number of factors other than the weather that may have an even greater impact on revenue. In addition, some of these companies operate outside of Europe, and thus are exposed to weather events outside of the analysis region. Finally, as mentioned before, the method of calculating the average annual values, while appropriate for the scale and timeline of this research, does wash out much of the variability across Europe. More advanced statistical techniques for analyzing systems with this many variables may be more appropriate.

The goal of the annual reports was to gain an understanding of the risk management techniques of companies that operate renewable power stations. Large companies were chosen because larger, more diversified companies had a higher probability of using weather derivatives, even if it was just for gas demand hedging. In addition, the annual reports at those companies were readily available. Some of the smaller renewable-only companies I encountered were not public, and thus were not obligated to provide this information. This did provide interesting information, and I think the results can be applied not just to the UK, but also to similar companies worldwide, given the size of the companies and the fact that they operate over a wide area. However, this is only because the information gathered was so general. Reviewing companies that operate solely renewable power stations would have been more targeted to the goals of this thesis.

Finally, on to the subject of interviews. On the weather derivative side of the interview pool was satisfactory with both the number and quality of interviews conducted. Randalls (2006) cited the 'saturation principle' (Schoenberger 1991) when determining when he had reached the appropriate number of interviews. All those on the finance side seemed to support and agree with each other to the point that I believe this threshold has been met, which seems reasonable given the small size of the weather derivatives market. I don't believe that this was achieved for the other actors such as developers, investors, and sellers. The goal here was to cast a wide net to bring in ideas from all actor types in this area on how the weather derivative market, and investment in renewable energy works and I think that was achieved. These interviewees provided valuable information, stories, and opinions that helped to support the theoretical framework and sometimes corroborate or refute other information gathered. However, this thesis can draw few widespread conclusions about the attitudes of these actor groups other than it would be a very interesting area for future research.

## 6.5 Future Research

Weather derivatives are still a relatively new product, and while there have been many papers looking at temperature contracts, price, and demand, few have looked at supply risk and renewable energy, and even fewer have looked at the implications of this risk management option on investment for renewable energy. This research only puts a small dent in this area, but from this a few avenues of future research become apparent.

As stated in the previous section more research needs to be done on the attitudes of developers and investors in this area. Depending on their background, I expect to see a wide range of opinions on this topic in both camps. The results of talking with a developer indicate that there is at least some distrust of these exotic derivative products. During interviews these products were referred to solely has derivatives. It would be interesting to see how investors and developers react to these weather hedges when they are structured and marketed more like insurance versus a financial derivative. More in depth interviews with investors and their knowledge on these products would also be very beneficial. Those interviewing individuals in these categories should be careful in their initial contact to frame the description of their research in such a way that potential interviewees won't self-exclude themselves for not being knowledgeable enough.

The subject of climate change was brought up during the interviews, but was not a major topic in this research. This risk was acknowledged, but did not cause serious concern among most interviewees. I'm sure some attempts to quantify this risk using modeling have already been done, most likely in relation to the latest IPCC report[9]. Some interviewees mentioned that this was taken into account when making models and contracts. It would be interesting to examine how this is taken into account and to see what extent climate change adaptation has become part of the planning and investment process for new capital projects like power plants.

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[9] I would expect to find this type of research in Working Group III: Impacts, Adaptation, and Vulnerability, part of the 5th Assessment Report, or AR5.

Finally, in the future, if and when weather derivatives are used regularly by renewable energy companies to hedge against weather vulnerability, an objective study to determine the effectiveness of these products should be carried out. I envision a study similar to the one by Pérez-González and Yun (2013), that calculate the effect of weather derivatives on firm value. Similar to the quantitative analysis performed here, but following their entire procedure rather than a subsection of it. Pérez-González and Yun's technique is attractive because doesn't matter exactly what contracts are used by companies, which is useful given the customization in OTC contracts. It does however require a number of companies to use these products regularly over a fairly long period of time. So, given the current state of the market, this analysis could not be carried out for many years.

# 7. Conclusion

Renewable energy is an important part of the energy mix of many countries, and as time goes on it will grow more important as economies around the world reduce their use of carbon based energy sources. Large private investment is necessary to achieve the targets desired by policy makers (Painuly 2001). However, such investments do not come without risk, and renewable energy projects such as wind and solar are already at a disadvantage compared to conventional energy (Wüstenhagen and Menichetti 2012). One such risk, is the risk that comes from small variations in climate, like a mild winter or a rainy summer. While a relatively new product, weather derivatives, have proven their ability to help manage these types of risk for conventional energy companies and improve the financial situation of many of the firms that use them (Pérez-Gonzáles and Yun 2013). Little formal research has been done to examine how these products could be used to the benefit of renewable energy companies, or what, if any, effect this may have on investment. This thesis has examined the extent to which renewable weather companies are vulnerable to the weather, the mechanisms by which the use of weather derivatives could impact investment, and the current state of the weather derivatives market.

A wide range of research techniques were utilized to attempt to gain a better understanding of this somewhat opaque field of weather risk management including statistical analysis, interviews, and reviews of company reports. Any one of these could, in theory, have been the focus of a research paper, each having its own strengths and limitations. This multifaceted approach was chosen because of the difficulty in obtaining data for each technique. Randalls (2006) was used as a guide in designing much of the methodology because of his detailed account of the difficulties of doing research in this area. The goal being that where one technique was lacking adequate coverage of a topic, the others would be able to fill in gaps in knowledge. The success of this technique was limited, but meaningful results can still be gleaned from this analysis.

Undoubtedly, the power output from renewable power stations are affected by the weather. Fluctuations in renewable energy supply, which can also affect the price of electricity, impacts the performance of the companies who operate them. The results of a statistical analysis adapted from Pérez-Gonzáles and Yun (2013), which was originally used to calculate the weather-induced volatility in revenue of conventional energy companies were inconclusive. The numbers showed surprisingly little correlation between income and the volatility in cloud cover, wind speed, or precipitation, which could be explained by any number of reasons. However, some of the assumptions upon which this analysis is based ultimately did not hold up, so the numbers must be treated with caution. While it was not the subject of the initial literature review, the topic of renewable energy's effect on spot market prices came up in several interviews. The volatility introduced into this market in this fashion exposes conventional energy companies to similar types of weather risk as the renewables on the grid, potentially making them players in the same section of the weather derivatives market. The exact extent of this effect, in monetary or statistical terms, remains unclear, but it is a concern shared by many in this area.

Weather derivatives can increase investment through the mechanism described in Pérez-Gonzáles and Yun (2013). Weather derivatives set a floor on revenue. This means that companies will be able to service their debt regardless of the amount of power produced, and debt providers can offer better financial terms because of this minimum. This guarantee on revenue also means that companies need less cash on hand and are able to take on more debt, freeing up more resources for investment. While it is not common, this aspect is not even completely theoretical, one interviewee described a situation in the recent past where a bank included weather derivative clauses in a few of their financing packages for renewable energy projects. The use of weather derivative products may also reduce the perceived risk of the project to potential investors, affecting investment in the was described by Wüstenhagen and Menichetti's (2012).

The use of these products is one of the most interesting pieces of information gathered during this research. Wind, solar, and even rainfall are not widely used weather derivative products. Although rainfall is more common than the others. Furthermore, in the instances when they are used, it may not be by renewable energy companies, but rather more traditional energy companies trying to hedge their curtailment risk. This contradicts several articles in the literature that claim that these are common contracts. While the annual reports reviewed leave open the possibility that these contracts are being used, many of the interviewees say that it is relatively rare. Temperature contracts are still the primary derivatives traded in the weather markets, but those are designed to deal with demand. Many reasons were cited for this lack of use including immaturity of the market, price, too much regulation and subsidization, and a lack of knowledge. There was also one instance of skepticism of derivatives seen, which would be interesting to explore in future research.

The update on the current state of the normally very closed weather derivatives market is perhaps the most useful conclusion to come from this thesis, as is the evidence that weather derivatives have had an effect on financing for renewable energy projects, even if they are only isolated examples. Questions about the extent of the weather exposure of the renewable industry were not answered satisfactorily, and leave open the need for more quantitative research in the future. More qualitative research is also recommended into the opinions of renewable developers, investors, and operators towards weather risk and weather derivatives. The suspicions of this researcher from this experience is that there is a diverse range, but the size of the interview pool did not allow for that analysis to be performed here.

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# Personal Communications

Advisor at an environmental investment firm. Email. May 2014.

Analyst at energy trading company. Formal Interview. 3 April 2014.

CEO of met. data and consultancy company(meteorological data, software and consultancy company). Skype. 23 April 2014.

CEO at a renewable energy company. Email. May 2014.

Consultant at a wind modeling company. Email. March 2014.

Director of investment organization. Executive director at a non-profit specializing in investment risk. Email. May 2014.

Originator at reinsurance company. Formal Interview. 16 April 2014.

Partner at insurance broker. Skype. April 2014.

President of a renewable energy development company. Skype. May 2014.

Weather derivative team lead at an energy company (the trading division of an electric utility). Formal Interview. 16 April 2014.

# Appendix I : Weather Data Processing

This appendix contains copied of three programs used to read in the ERI-Interim data.

The programs contain descriptions on their function and use as well an annotations.

## Area_avg.csh

```
#! /bin/csh -f
########################################################################
# Perfoms areal averaging of data using NetCDF Operators for all
# NetCDF files in a directory. Output will go into a new
# directory called area_averaged. It also calculates the wind
# speed from a directory called wind_comp.
#
# Aaron Perry May 20, 2014
#
# Usage: $ ./area_avg.csh
########################################################################

# Make directory for output to go in
mkdir area_averaged

# Combine u and v wind components into single file
ncks -A ./wind_comp/uwind00z00122002-2013.nc ./wind_comp/vwind00z12z2002-2013.nc
echo "Wind vectors merged"

# Calculate wind speed from vectors
ncap2 -O -s "w_speed=sqrt(u10^2+v10^2)" ./wind_comp/vwind00z12z2002-2013.nc ./wind00z12z2002-2013.nc
echo "Wind Speed Calculated"

# Perform areal average
foreach file (./*.nc)
	ncwa -a latitude,longitude $file ./area_averaged/$file
	echo "$file averaged"
end
```

## annual_averages.csh

```
#! /bin/csh -f
#########################################################################
# Extracts each year from NetCDF file starting with 2013 and going
#  until 2004, taking into account leap years.
#
# Aaron Perry May 20, 2014
#
# Usage: $ ./annual_averages.csh file.nc variable_name
#########################################################################
# Read in command line arguments
  if ($#argv != 2) then
    echo "Usage: $0 file.nc variable"
            exit
  endif
  ##        save command line arguments
  set file=$1
  set var=$2

# Make director for output
mkdir annual_averages

# Number of hours in a year and leap year
set hrs_in_ry = 730
set hrs_in_ly = 732

set time_end = 8765 #last value of time from netcdf file

# Seperate out files into the their respective years by counting backwards
@ time_start = $time_end - $hrs_in_ry - 1

ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2013.nc"

@ time_start = $time_start - $hrs_in_ly
@ time_end = $time_end - $hrs_in_ry
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2012.nc"

@ time_start = $time_start - $hrs_in_ry
@ time_end = $time_end - $hrs_in_ly
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2011.nc"

@ time_start = $time_start - $hrs_in_ry
@ time_end = $time_end - $hrs_in_ry
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2010.nc"

@ time_start = $time_start - $hrs_in_ry
@ time_end = $time_end - $hrs_in_ry
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2009.nc"

@ time_start = $time_start - $hrs_in_ly
@ time_end = $time_end - $hrs_in_ry
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2008.nc"

@ time_start = $time_start - $hrs_in_ry
@ time_end = $time_end - $hrs_in_ly
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2007.nc"

@ time_start = $time_start - $hrs_in_ry
@ time_end = $time_end - $hrs_in_ry
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2006.nc"
```

```
@ time_start = $time_start - $hrs_in_ry
@ time_end = $time_end - $hrs_in_ry
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2005.nc"

@ time_start = $time_start - $hrs_in_ly
@ time_end = $time_end - $hrs_in_ry
ncks -d time,$time_start,$time_end $file ./annual_averages/"$var""_2004.nc"

# Make directory for next output
mkdir ./annual_averages/final_annual_avg

# Move to annual_averages directory
cd annual_averages

# Calculate annual averages
foreach sub_file ("$var"*.nc)
        ncwa -a time $sub_file final_annual_avg/$sub_file
        echo "$sub_file averaged"

cd ..
end
```

# Appendix II

The following is a description of some of the additional statistics performed on the ERA-Interim time series obtained from the ECMWF. Since the standard deviation calculation was going to use the entire [12 year, 12 hour time steps] time series downloaded rather than annual averages or a small portion of the data I checked to see if assumptions of normality were held and if there was a significant trend in the data. To accomplish this an NCL program was written to draw a histogram, plot the data, perform a regression and calculate the significance, and the Durbin-Watson test for autocorrelation.

Figures A1 and A2 show a histogram of the distribution of the data and scatter plot with trend line. Table A1 shows the t-test for the regression, with the null hypothesis being that the regression is zero, and the results of the Durbin-Watson test which show that there is positive autocorrelation within the data[10]. This means the standard deviation values calculated are biased. As mentioned in the main body of the text the detrend function was used to remove the trend from the total precipitation and the total cloud cover prior to the standard deviation calculations.

In future analysis, with finer timescales and more data than one year for all of the data, seasonality, trends, normality, and autocorrelation will be more of a concern.



**Table A1. Results of T-test and Durbin-Watson test**

| | T-test score | D-W Statistic |
|---|---|---|
| **Wind Speed** | -0.16 | 0.26 |
| **Total Cloud Cover** | 3.56 | 0.20 |
| **Total Precipitation** | 8.75 | 0.40 |

[10] Anderson, D. R., Sweeney, D. J., and Williams, T. A. 1990. *Statistics for business and economics.* 4th edition. Saint Paul: West Publishing Company.

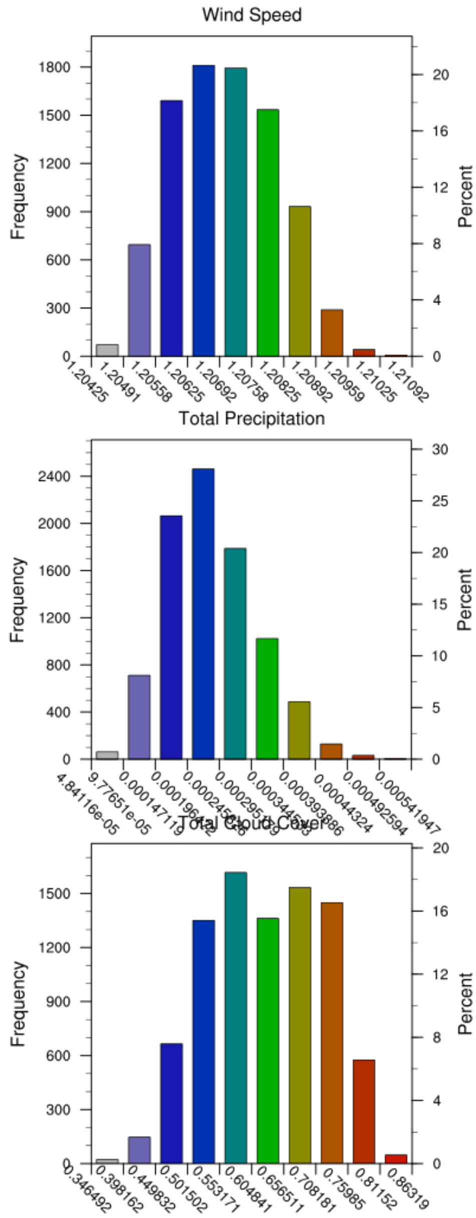


**Figure A1. Histogram of weather data (2002-2013). Data source: ECMWF**

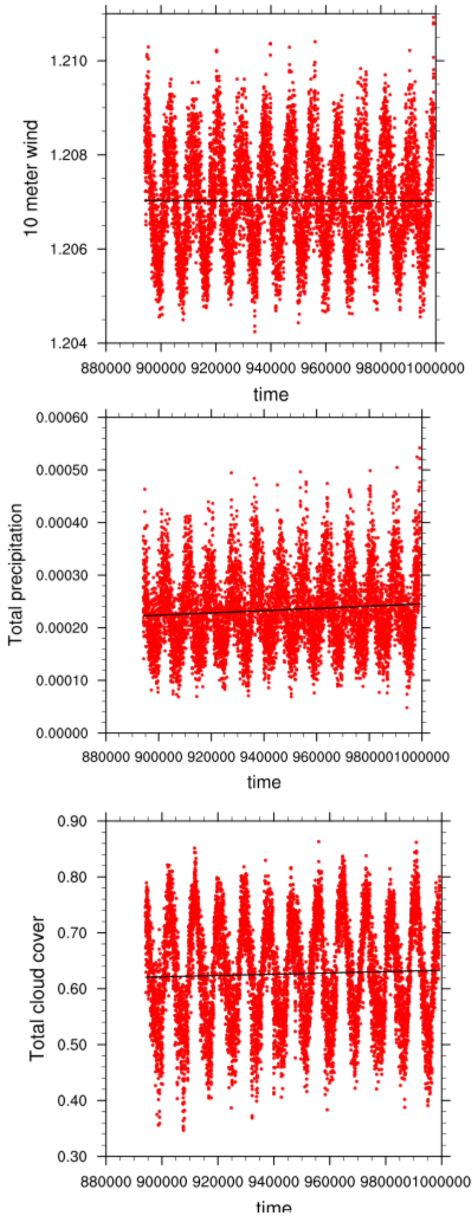


**Figure A2. Scatter plot of 12 hour weather data with trend line. Data source ECMWF.**



## trend.nc

```
;***************************************************
; trend.ncl
;
; Based on scatter_4.ncl which can be found at the
;   following url,
;   http://www.ncl.ucar.edu/Applications/Scripts/scatter_4.ncl
;
;***************************************************
```

```
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_csm.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/contributed.ncl"

begin
;************************************************
; Create pointer to files and read in data.
;************************************************
  file1  = addfile("wind00z12z2002-2013.nc","r")
  file2  = addfile("tp00z12z2002-2013.nc","r")
  file3  = addfile("tcloud00Z12Z2002-2013.nc","r")

  ws  = file1->w_speed(:)
  tp  = file2->tp(:)
  tc  = file3->tcc(:)

  data = (/ws, tp, tc/)

  timecoor = ws&time

;************************************************
; Abritrary Time Series of data
;************************************************

  x     = ispan(0,dimsizes(ws)-1,1)*1

;************************************************
; create histograms - before
;************************************************
 wks1 = gsn_open_wks("png","histo")            ; open workstation
 gsn_define_colormap(wks1,"temp1")             ; choose colormap

 plot1 = new(3,graphic)

 res1                          = True
 res1@gsnDraw                  = False
 res1@gsnFrame                 = False
 res1@gsnMaximize         = True                  ; maximize plot in frame
 res1@gsnHistogramSelectNiceIntervals = False   ; intervals now float
 res1@gsnHistogramComputePercentages  = True    ; change left axis to %
 res1@tmXBLabelAngleF                 = 315.    ; change label angle

 res1@tiMainString                   = "Wind Speed"
 plot1(0)=gsn_histogram(wks1,data(0,:),res1)         ; create histogram with 10 bins
 res1@tiMainString                   = "Total Precipitation"
 plot1(1)=gsn_histogram(wks1,data(1,:),res1)         ; create histogram with 10 bins
 res1@tiMainString                   = "Total Cloud Cover"
 plot1(2)=gsn_histogram(wks1,data(2,:),res1)         ; create histogram with 10 bins

 gsn_panel(wks1,plot1,(/3,1/),False)

;************************************************
; Regression
;************************************************

  ws_regB  = regline(x,ws)
          print(ws_regB)
  tp_regB  = regline(x,tp)
          print(tp_regB)
  tc_regB  = regline(x,tc)
          print(tc_regB)
```

```
ws_regBdata      = new ( (/2,dimsizes(ws)/), typeof(ws))
ws_regBdata(0,:) = ws
ws_regBdata(1,:) = ws_regB*(x-ws_regB@xave) + ws_regB@yave


tp_regBdata      = new ( (/2,dimsizes(tp)/), typeof(tp))
tp_regBdata(0,:) = tp
tp_regBdata(1,:) = tp_regB*(x-tp_regB@xave) + tp_regB@yave

tc_regBdata      = new ( (/2,dimsizes(tc)/), typeof(tc))
tc_regBdata(0,:) = tc
tc_regBdata(1,:) = tc_regB*(x-tc_regB@xave) + tc_regB@yave

;************************************************
; plotting parameters
;************************************************
 wks2  = gsn_open_wks ("png","scatter")           ; open workstation

 plot2 = new(3, graphic)

 ws@long_name = "10 meter wind"
 ws_regBdata@long_name = "10 meter wind"

 res2                  = True                     ; plot mods desired
 res2@gsnDraw                 = False
 res2@gsnFrame                = False
 res2@gsnMaximize         = True                  ; maximize plot in frame
 res2@xyMarkLineModes     = (/"Markers","Lines"/)  ; choose which have markers
 res2@xyMarkers           = 16                    ; choose type of marker
 res2@xyMarkerColor       = "red"                 ; Marker color
 res2@xyMarkerSizeF       = 0.005                 ; Marker size (default 0.01)
 res2@xyDashPatterns      = 1                     ; solid line
 res2@xyLineThicknesses   = (/1,2/)               ; set second line to 2

 plot2(0)  = gsn_csm_xy (wks2,ws&time,ws_regBdata,res2)                  ; create plot
 plot2(1)  = gsn_csm_xy (wks2,tp&time,tp_regBdata,res2)                  ; create plot
 plot2(2)  = gsn_csm_xy (wks2,tc&time,tc_regBdata,res2)                  ; create plot

 gsn_panel(wks2,plot2,(/3,1/),False)

;************************************************
; Durbin-Watson Statistic
;************************************************
  timesteps = dimsizes(ws)
  ws_error = ws(:) - ws_regBdata(1,:)
  tp_error = tp(:) - tp_regBdata(1,:)
  tc_error = tc(:) - tc_regBdata(1,:)

  ws_dwsN = new((/timesteps/), double)
  ws_dwsD = new((/timesteps/), double)

  tp_dwsN = new((/timesteps/), double)
  tp_dwsD = new((/timesteps/), double)

  tc_dwsN = new((/timesteps/), double)
  tc_dwsD = new((/timesteps/), double)

  do it=1,timesteps-1
        ws_dwsN(it) = (ws_error(it)-ws_error(it-1))^2
        ws_dwsD(it-1) = (ws_error(it-1)^2)

        tp_dwsN(it) = (tp_error(it)-tp_error(it-1))^2
```

```
            tp_dwsD(it-1) = (tp_error(it-1)^2)

            tc_dwsN(it) = (tc_error(it)-tc_error(it-1))^2
            tc_dwsD(it-1) = (tc_error(it-1)^2)
  end do

  ws_dws = sum(ws_dwsN(:))/sum(ws_dwsD(:))
  tp_dws = sum(tp_dwsN(:))/sum(tp_dwsD(:))
  tc_dws = sum(tc_dwsN(:))/sum(tc_dwsD(:))

  print(ws_dws)
  print(tp_dws)
  print(tc_dws)

;************************************************
; detrend
;************************************************

  tpDetrend  = dtrend(tp,True)
  tcDetrend  = dtrend(tc,True)

  tpDetrend!0 = "time"
  tcDetrend!0 = "time"

  tpDetrend&time= timecoor
  tpDetrend&time= timecoor

print("***************after detrending*****************")

  tpDstdev = stddev(tpDetrend)
  windstdev = stddev(ws)
  tcDstdev = stddev(tcDetrend)

  print(tpDstdev)
  print(tcDstdev)
  print(windstdev)

;*********************************************
end
```

# Appendix III : Regression and Correlation Calculations

```
######################################################################
# Regress_correl.py
#
# Reads in data from csv files created from data output from
# area_avg.csh, wind_stddev [ncl], and annual_averages.csh, and
# computes the following regression.
#
#   income/assets = a + b*weather + c*ln(assets) + e
#
# The b value is then multiplied by the standard deviation of the
# assocated weather value and a correlation is performed with the
# standard deviation of income.
#
# Author: Aaron Perry
# Date: May 21, 2014
#
# Usage: $ python Regress_correl.py
######################################################################

### Import required modules ###
import numpy as np
import pandas as pd
from pandas import *
import csv
import scikits.statsmodels.api as sm
import statsmodels.api as sm
import matplotlib.pyplot as plt
import math
import scipy

### Initialize variables ###
cloudCover = []
windSpeed = []
totalPrecip = []
companies = []
lnAssets = []
lnAssetstemp = []
iaratio = []
iaratiotemp = []
b_cloud = []
b_wind = []
b_precip = []
cloud_invol = []
wind_invol = []
precip_invol = []

### Read in weather data and append to appropriate variables ###
with open('Regression-weather.csv', 'rb') as csvfile:
        weather = csv.reader(csvfile, delimiter=',', quotechar='|')
        next(weather)
        for row in weather:
                cloudCover.append(float(row[1]))
                windSpeed.append(float(row[2]))
                totalPrecip.append(float(row[3]))

### Read in natural log of assets and income to assets ratio values ###
```

```
lnAssets = pd.read_csv('Regression-ln_of_assets.csv')
lnAssets.head()

iaratio = pd.read_csv('Regression-incomeassetsratio.csv')
iaratio.head()

### Perform multiple regression on weather, incomeassets, and lnAssets variables ###
# Cloud Cover
for icompany in range(1,46):
	x = np.column_stack((cloudCover,lnAssets.iloc[:,icompany])) #stack explanatory variables into an array
	x = sm.add_constant(x, prepend=True) #add a constant

	res = sm.OLS(iaratio.iloc[:,icompany],x,missing='drop').fit() #create a model and fit it

	b_cloud.append(abs(res.params[1])) #append b value into variable

	del x  #reinitialize variables
	del res

# Wind Speed
for icompany in range(1,46):
	x = np.column_stack((windSpeed,lnAssets.iloc[:,icompany])) #stack explanatory variables into an array
	x = sm.add_constant(x, prepend=True) #add a constant

	res = sm.OLS(iaratio.iloc[:,icompany],x,missing='drop').fit() #create a model and fit it

	b_wind.append(abs(res.params[1])) #append b value into variable

	del x  #reinitialize variables
	del res

# Precipitation
for icompany in range(1,46):
	x = np.column_stack((totalPrecip,lnAssets.iloc[:,icompany])) #stack explanatory variables into an array
	x = sm.add_constant(x, prepend=True) #add a constant

	res = sm.OLS(iaratio.iloc[:,icompany],x,missing='drop').fit() #create a model and fit it

	b_precip.append(abs(res.params[1])) #append b value into variable

	del x  #reinitialize variables
	del res
### Multiply b values by appropriate standard deviations, and take absolute value ###
for j in range(0,44):
	cloud_invol.append(math.fabs(b_cloud[j]*0.001054513))
	wind_invol.append(math.fabs(b_wind[j]*0.001054513))
	precip_invol.append(math.fabs(b_precip[j]*0.001054513))

### Read in income volatility values ###
incVoltemp = pd.read_csv('income_vol.csv')
incVoltemp.head()
incVol = incVoltemp.iloc[:,1:45]

### Move weather variables into data frame to match finance data ###
cloud_involdf = DataFrame(cloud_invol)
wind_involdf = DataFrame(wind_invol)
precip_involdf = DataFrame(precip_invol)

### Transpose 2D arrays
cloud_involdfT = cloud_involdf.T
wind_involdfT = wind_involdf.T
precip_involdfT = precip_involdf.T
```

```
### Calculate and display descriptive statistics ###
print " N  Mean       Std-Dev.       Min       Median       Max"
print len(incVol.T), np.nanmean(incVol.T), np.nanstd(incVol.T), np.nanmin(incVol.T), np.median(incVol.T),
np.nanmax(incVol.T)
print len(b_cloud), np.nanmean(b_cloud), np.nanstd(b_cloud), np.nanmin(b_cloud), np.median(b_cloud),
np.nanmax(b_cloud)
print len(b_wind), np.nanmean(b_wind), np.nanstd(b_wind), np.nanmin(b_wind), np.median(b_wind),
np.nanmax(b_wind)
print len(b_precip), np.nanmean(b_precip), np.nanstd(b_precip), np.nanmin(b_precip), np.median(b_precip),
np.nanmax(b_precip)
print len(cloud_invol), np.nanmean(cloud_invol), np.nanstd(cloud_invol), np.nanmin(cloud_invol),
np.median(cloud_invol), np.nanmax(cloud_invol)
print len(wind_invol), np.nanmean(wind_invol), np.nanstd(wind_invol), np.nanmin(wind_invol),
np.median(wind_invol), np.nanmax(wind_invol)
print len(precip_invol), np.nanmean(precip_invol), np.nanstd(precip_invol), np.nanmin(precip_invol),
np.median(precip_invol), np.nanmax(precip_invol)

### Calculate correlation coefficients and display values ###
test = np.corrcoef(incVol,cloud_involdf.T)
print "income versus cloud"
print test

test2 = np.corrcoef(incVol,wind_involdf.T)
print "income versus wind"
print test2

test3 = np.corrcoef(incVol,precip_involdf.T)
print "income versus precip"
print test3

print "######## EXTRA TESTS ##########"

test4 = np.corrcoef(cloud_involdf.T,wind_involdf.T)
print "cloud versus wind"
print test4

test5 = np.corrcoef(cloud_involdf.T,precip_involdf.T)
print "cloud versus precip"
print test5

test6 = np.corrcoef(wind_involdf.T,precip_involdf.T)
print "wind versus precip"
print test6


incVolT = incVol.T # transpose for normal tests

### Test for normalcy of variables ###
zi,pvali = scipy.stats.mstats.normaltest(incVol.T)
print 'income'
if(pvali < 0.055):
  print " -> Not normal distribution"

zc,pvalc = scipy.stats.mstats.normaltest(cloud_involdf)
print 'cloud'
if(pvalc < 0.055):
  print " -> Not normal distribution"

zw,pvalw = scipy.stats.mstats.normaltest(wind_involdf)
print 'wind'
if(pvalw < 0.055):
```

```
  print " -> Not normal distribution"

zp,pvalp = scipy.stats.mstats.normaltest(precip_involdf)
print 'precip'
if(pvalp < 0.055):
  print " -> Not normal distribution"

###END###
```