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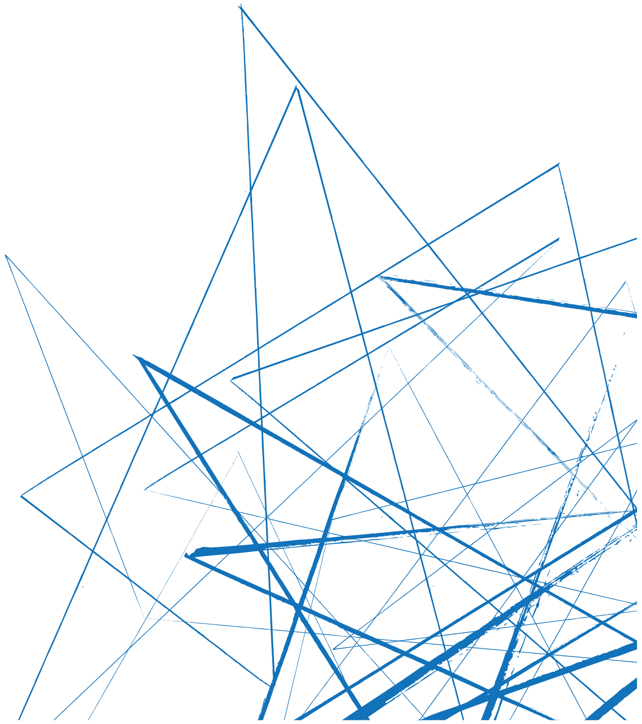

OPPORTUNITIES AND RISKS IN ALTERNATIVE INVESTMENTS

PhD Series 36.2021

Alexander Kronies

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CBS PhD School

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CBS COPENHAGEN BUSINESS SCHOOL
HANDELSHØJSKOLEN

Opportunities and Risks in Alternative Investments

Alexander Kronies

A thesis presented for the degree of
Doctor of Philosophy

Supervisor: Ken L. Bechmann
Ph.D. School in Economics and Management
Copenhagen Business School

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Abstract

This thesis revolves around the quantification of opportunities and risks in alternative investments. The first chapter is on the topic of asset pricing, whereas the second and third chapter concern energy finance. Each chapter can be read independently.

The first chapter considers skills and preferences of different types of investors when investing sustainably. We document a positive environmental, social, and governance (ESG) premium among stocks with non-ESG-motivated ownership, which we attribute to the investors' unique skill to forecast future ESG scores. When higher ESG scores materialize, ESG-motivated investors buy stocks of these firms, which pushes up the price and gives low returns going forward. The ESG premium under non-ESG-motivated ownership is stronger during periods of high climate sentiment. We explain these results by a theory of sustainable investing with heterogeneous skill and sustainability sentiment.

The second chapter researches correlation dynamics between wind energy production and electricity prices. I show that large turbines outperform their smaller peers. That is, large turbines produce more and with higher persistence over time. Also, production outputs are less negatively correlated to electricity prices, which puts them in a position in which they yield a higher average price per production unit. This effect is especially pronounced during high and low production times. Additional tests on high-frequency data confirm these results and provide evidence that the realized price effects from negative correlations between production and electricity prices are much larger than monthly data suggests and economically meaningful.

The third chapter develops a novel theoretical approach to value wind energy investments with a special focus on a Danish policy change concerning subsidy systems. The model incorporates risk exposures to a number of relevant parameters and especially considers uncertainty in subsidy distributions over time. I use the approach to model investment opportunities in wind energy through a Monte Carlo simulation and provide more clarity on which risk factors matter most. I further show that small structural changes in subsidy specifications can have significant impacts on investment decisions by private investors and therefore capital allocations at large.

Acknowledgments

This thesis represents the final product of my PhD studies at the Department of Finance and Pension Research Centre at Copenhagen Business School. Throughout my time as a PhD student I received tremendous support from far more people than I could possibly mention here. The least I can do is acknowledge those that deserve special recognition.

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Finally, I would like to take the opportunity to thank my family. Their unconditional love and continuous support throughout the years have been invaluable to me. I will forever be in their debt and I would like to dedicate this thesis to them.

Alexander Kronies

Copenhagen, September 2021

Summaries in English

Skills and Sentiment in Sustainable Investing

with Andreas Brøgger

This essay researches investors with heterogeneous preferences and skills when allocating capital to sustainable firms, where the level of sustainability is defined by the firms' individual Environmental, Social, and Governance (ESG) score. Specifically, we follow an approach by Hong and Kacperczyk (2009) and consider two types of investors. Referred to as socially constrained, we study investors who are subject to mandates to invest sustainably. Socially unconstrained investors, on the other hand, are not subject to any restrictions or guiding principals other than risk and return considerations. We document how these socially unconstrained investors are able to capitalize on unique skills to exploit sustainability sentiment in the equity market.

First, we show that socially unconstrained investors exploit an ESG premium. Specifically, firms with high socially unconstrained ownership and high ESG scores pay high returns. A long-short strategy going long in high ESG and high unconstrained ownership firms and going short in low ESG and high unconstrained ownership firms yields positive and significant abnormal returns. Socially constrained investors however are not capable to exploit this ESG premium. Instead, they chase high return and high ESG score firms, but once bought, high returns vanish.

Second, we find that socially unconstrained investors are able to predict positive ESG score increases, whereas socially constrained investors are not. This skill to predict positive ESG score increases earns socially unconstrained investors additional return. Once firms' ESG scores increase, they become available to constrained investors too, who push up the price. Unconstrained investors capitalize on this increased demand and sell these firms' shares to constrained investors.

Third, we show that ESG premiums are positively correlated to sentiment. We create our own measure by using the output by Google hits on the term 'Climate Change'. Additionally, we use other sentiment measures as developed by Engle et al. (2020) and Baker and Wurgler (2006). We document that both a general ESG premium and one that roots in firms with high unconstrained ownership are driven by sustainability and market sentiment.

Our findings can be explained by a theory of sustainable investing with skill. Proving this formally, we introduce skill and sustainability sentiment to the standard Capital Asset Pricing Model (CAPM). We built on previous work by Pástor et al. (2021), but allow skilled investors to predict future ESG scores. Our work is the first to provide empirical facts on not only our own model but also other theoretical research revolving around sustainable investing.

The Bigger the Better?

The second essay investigates correlation dynamics between wind energy production and electricity prices. This is important to consider when allocating capital to this asset class as the interconnection between production and prices largely impacts expected returns. If neglected, investors might either over- or underestimate future cash flows depending on whether correlations are positive or negative.

Specifically, I study a large sample of turbine-individual production data in the Danish DK1 and DK2 markets[1] on a monthly granularity and empirically investigate the impact of correlations to electricity prices on capture rates across capacity levels. Additionally, I utilize high-frequency data provided by a private Danish investor that documents production and wind-speed information across a total of 81 turbines.

A time-series analysis shows that large turbines are not only less volatile in their production dynamics but also, they are, on average, less negatively correlated to electricity prices. This puts them in a superior position against smaller turbines due to the fact that they capture a higher average price per production unit. This makes larger turbines yield higher risk-adjusted returns considering all else being equal. This pattern is especially pronounced in high- and low-production times. This means that when small turbines experience low-production times, prices are especially high, and vice versa, which is true for large turbines as well but to a significantly lesser extent. Panel regressions confirm these findings when controlling for lagged prices and the market consumption of electricity.

The analysis with high-frequency data confirms these findings, meaning that large turbines capture higher average electricity prices compared to their smaller peers. However, the high-frequency analysis additionally reveals that the effects from negative correlations between power prices and production are much larger than the monthly data indicates. The findings suggest that investors should, on average, expect a captured electricity price, which is 16% below the average price under the production profile of large turbines and 12% below under small turbine production.

These findings underscore the relevance for investors to consider correlation dynamics between power production and electricity prices when allocating capital to energy assets. Especially the

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[1] The DK1 market depicts the western price area of Denmark, whereas the DK2 market represents the eastern price area.

high-frequency data stresses that this effect can have major implications for a project's risk and return profile. All else equal, investors would be better off owning a share in a large turbine.

The Value of Renewable Energy and Subsidies: An Investor's Perspective

The final essay develops a novel approach to value wind energy investments under different subsidy schemes in Denmark, that is, additional compensation by the federal government to encourage private capital to flow into green energy. I use this approach to exhibit and quantify key value drivers of such projects and determine their fundamental value. Findings of this study are relevant not only for academics but also for practitioners, who aim to obtain a more granular perspective on long-term investments in wind energy.

Specifically, my model considers two types of subsidy schemes, one which I refer to as the old and one which I refer to as the new scheme. Also, I consider a base case under which an investor does not receive any additional subsidy compensation. The old subsidy scheme grants an investor a defined contribution for every megawatt-hour (MWh) of green energy production for a given number of hours. The new scheme, however, is a technology-neutral tender-based system, under which investors place bids to receive future contributions for new projects and for a defined number of years.

In the model, I choose to vary wind speeds, discount rates, uncertainty in subsidy distributions and bids under the tender-based scheme. Also, I vary electricity price growth forecasts based on work by Lucia and Schwartz (2002) and Seifert and Uhrig-Homburg (2007). I run a Monte Carlo simulation to determine risk and return profiles of a hypothetical investment opportunity under a base case and varying scenarios.

I present three key findings. First, I document that small variations in subsidy schemes can have major implications to investors and therefore the allocation of capital. Second, I find that long-duration wind energy assets are largely exposed to minor changes in wind speeds, electricity price forecasts, and uncertainty in subsidy distributions. Finally, I show that under the new subsidy scheme, investors, on average, are worse off due to less distributions relative to the old scheme. Also, competition with other investors and technologies decreases expected bids as already seen in the first tender.

These findings are important to not only investors, policy-makers and academics in Denmark but across other countries too. I document the key drivers with respect to risk and return in this asset class and show how one can think of subsidy distributions under uncertainty. Finally, the proposed model is also applicable to other markets and subsidy schemes through simple adjustments.

Summaries in Danish

Skills and Sentiment in Sustainable Investing

med Andreas Brøgger

Dette essay undersøger investorer med heterogene færdigheder og præferencer, når de allokerer kapital til bæredygtige virksomheder, hvor bæredygtighedsniveauet er defineret af virksomhedernes individuelle score for Environmental, Social og Governance (ESG). Helt konkret følger vi en tilgang fra Hong and Kacperczyk (2009) og overvejer to typer af investorer. Omtalt som socialt begrænset, studerer vi investorer, der er underlagt mandater til at investere bæredygtigt. Socialt ubegrænsede investorer er derimod ikke underlagt andre restriktioner eller vejledende principper end risiko- og afkastovervejelser. Vi dokumenterer hvordan disse socialt ubegrænsede investorer er i stand til at udnytte unikke færdigheder til at udnytte interesse i bæredygtighed på aktiemarkedet.

For det første viser vi at socialt ubegrænsede investorer udnytter en ESG-præmie. Helt konkret giver virksomheder med et højt socialt ubegrænset ejerskab og høje ESG-scorer høje afkast. En lang-kort strategi, der går lang i høj ESG og høj ubegrænsede ejerskabsfirmaer og går kort i lav ESG og høj ubegrænset ejerskabsfirmaer, giver betydeligt positive anormale afkast. Socialt begrænsede investorer er imidlertid ikke i stand til at udnytte denne ESG-præmie. I stedet jagter de høje afkast og høje ESG-score virksomheder, men når de har købt forsvinder de høje afkast.

For det andet finder vi, at socialt ubegrænsede investorer er i stand til at forudsige positive ESG-scorestigninger, mens socialt begrænsede investorer ikke er det. Denne evne til at forudsige positive ESG-score stigninger, giver socialt ubegrænsede investorer ekstra afkast. Når virksomheders ESG-score stiger, bliver virksomheden tilgængelig for de begrænsede investorer, der derved er med til at presse prisen op. Ubegrænsede investorer udnytter denne øgede efterspørgsel og sælger derefter disse virksomheders aktier til de begrænsede investorer.

For det tredje viser vi, at ESG-præmier er positivt korreleret til bekymring omkring klimaet. Vi opretter vores eget mål ved at bruge målinger af Google-hits på udtrykket 'Climate Change'. Derudover bruger vi andre målinger, som er udviklet af Engle et al. (2020) og Baker and Wurgler (2006). Vi dokumenterer, at både en generel ESG-præmie og en, der har rødder i virksomheder med et stort ubegrænset ejerskab, er drevet af bæredygtigheds- og markedsinteresse.

Vores resultater kan forklares ved hjælp af en teori om bæredygtige investeringer med forskellige færdigheder. Når vi formelt beviser dette, introducerer vi dygtighed og bæredygtigheds-interesse til standard Capital Asset Pricing Model (CAPM). Vi byggede videre på tidligere arbejde af Pástor et al. (2021), hvor vi derudover giver kvalificerede investorer mulighed for at forudsige fremtidige ESG-scorer. Vores arbejde er det første, der giver empiriske fakta om ikke kun vores egen model, men også anden teoretisk forskning, der drejer sig om bæredygtige investeringer.

The Bigger the Better?

Det andet essay undersøger korrelationsdynamikker mellem vindenergiproduktion og elpriser. Det er vigtigt at tage hensyn til disse dynamikker, ved allokering af kapital til energi aktiver, da sammenhænge mellem produktion og priser påvirker forventede afkast. Hvis investorer ikke tager hensyn til disse dynamikker, over- eller underestimerer de muligvis fremtidige pengestrømme, afhængig af om korrelationerne er positive eller negative.

Jeg undersøger et stort datasæt indeholdende produktionsdata for individuelle vindmøller på de danske DK1 og DK2 markeder[2] på månedsbasis og undersøger empirisk effekten af korrelationer til elpriser på capture-rater på tværs af kapacitetsniveauer. Derudover benytter jeg højfrekvensdata, stillet til rådighed af en dansk investor, der dokumenterer produktions- og vindhastighedsinformation for 81 vindmøller.

En tidsrækkeanalyse viser, at store vindmøllers produktionsdynamikker ikke kun er mindre volatile men også mindre negativt korreleret med elpriser i gennemsnit. Dette sætter disse vindmøller i en fordelagtig position, i forhold til mindre vindmøller, eftersom de tilvejebringer en højere gennemsnitlig pris per produktionsenhed. Dette resulterer i højere risikojusterede afkast, alt andet lige. Dette mønster er især gældende i tidsperioder med høj eller lav produktion. Dette betyder at priserne er høje når små vindmøller oplever lav produktion, og vice versa, hvilket også er gældende for store vindmøller dog i signifikant mindre grad. Panel regressioner bekræfter disse resultater når man kontrollerer for tidligere priser og markedets forbrug af elektricitet.

Analysen med højfrekvensdata bekræfter disse resultater dvs. at større vindmøller tilvejebringer højere gennemsnitlige elpriser sammenlignet med mindre vindmøller. Højfrekvensdata-analysen viser imidlertid også at effekten af negativ korrelation mellem priser og produktion er større end månedlige data indikerer. Resultaterne tyder på at investorer, i gennemsnit, bør forvente en effektiv elpris 16% under den gennemsnitlige pris med produktionsprofilen for store vindmøller og 12% under for små vindmøller.

Disse resultater understøtter relevansen af at tage hensyn til korrelationsdynamikker mellem

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[2] DK1 markedet dækker det vestlige prisområde af Danmark mens DK2 markedet dækker det østlige prisområde.

energiproduktion og elpriser ved kapitalallokering til energi aktiver. Højfrekvensdata understreger at denne effekt kan have store implikationer for et projekts risiko- og afkastprofil. Investorer vil, alt andet lige, være bedre stillet ved en ejerandel i en stor vindmølle.

The Value of Renewable Energy and Subsidies: An Investor's Perspective

Dette kapitel udvikler en ny model til værdiansættelse af vindenergiinvesteringer under forskellige subsidieordninger i Danmark, der etableres fra politisk side for at tilskynde privat kapital til at investere i grøn energi. Modellen bruges til at kvantificere centrale værdidrivere af sådanne projekter og bestemme deres grundlæggende værdi. Resultaterne af denne undersøgelse er relevante ikke kun for akademikere, men også for praktikere, der har til formål at opnå et mere detaljeret perspektiv på langsigtede investeringer i vindenergi.

Specifikt behandles i modellen to typer subsidieordninger, der henholdsvis omtales som den gamle og den nye ordning. Endelig betragtes også en base case, hvor en investor ikke modtager nogen subsidier. Den gamle tilskudsordning giver en investor et fast bidrag for hver megawattime (MWh) grøn energi i et givet antal timer. Den nye ordning er et teknologineutralt udbudsbaseret system, hvor investorer for hvert projekt afgiver et bud på størrelsen af subsidier for en udmeldt periode.

I modellen analyseres betydningen af vindhastigheder, diskonteringssatser, usikkerhed i subsidieordninger og bud under den nye udbudsbaserede ordning. Endvidere inkluderes prognoser for elprisvækst baseret på arbejde udført af Lucia and Schwartz (2002) og Seifert and Uhrig-Homburg (2007). Monte Carlo-simulering bruges til at bestemme risiko- og afkastprofiler for en hypotetisk vindenergiinvestering under de to subsidieordninger sammenhold med et tilfælde uden subsider.

Kapitlet har tre hovedresultater. For det første dokumenteres, at små variationer i tilskudsordninger kan have store konsekvenser for investorer og dermed for investeringslysten. For det andet vises det, at vindenergiaktiver med lang varighed er følsom overfor selv mindre ændringer i vindhastigheder, elprisprognoser og usikkerhed om subsidieordninger. Endelig vises det, at investorer i gennemsnit er dårligere stillet under den nye subsidieordning på grund af mindre udbetalinger i forhold til den gamle ordning. Konkurrencen mellem investorer og med andre teknologier reducerer også de forventede bud som allerede set i de første udbud.

Disse resultater er ikke kun vigtige for investorer, politikere og forskere i Danmark, men også på tværs af andre lande. Resultaterne viser de vigtigste drivkræfter med hensyn til risiko og afkast i denne aktivklasse og angiver, hvordan man kan tænke på subsidieordninger under usikkerhed. Endelig kan den foreslåede model efter enkelte justeringer også anvendes på andre markeder og subsidieordninger.

Contents

Chapter 1

Skills and Sentiment in Sustainable Investing

with Andreas Brøgger

Abstract

We document a positive ESG premium among stocks with non-ESG-motivated investor ownership. ESG-motivated investors buy ESG stocks, which pushes up the price and gives low returns going forward. We show that a theory of sustainable investing with heterogeneous skill and sustainability sentiment can explain this finding. In support of this explanation, we find that non-ESG-motivated ownership leads to future ESG score increases, that ESG score increases improve returns, and that the non-ESG-motivated investor sells high ESG stocks to the ESG-motivated investor. The premium among high degrees of non-ESG-motivated ownership is stronger during periods of high climate sentiment.

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1 Introduction

The consequences of the sustainable investment boom are not yet well understood. Fundamentally, general equilibrium theory would tell us that a higher demand of sustainable stocks today should lead to reduced returns going forward (as in Pástor et al., 2021). On the other hand, Baker and Wurgler (2006) would argue that precisely because there is a high demand, this sentiment will yield high returns in the short term. Finally, a third view is that high returns could arise if environmental, social and governance (ESG) metrics are a hidden quality signal (Pedersen et al., 2020). In contrast, this paper shows a new and important channel. That is, if some skilled investors are able to predict future ESG scores, the demand for sustainable investments will lead to high returns as the improved ESG score materializes.

Sentiment is particularly relevant now as we consider the consequences of the unprecedented shift in capital allocation towards assets with an ESG focus.[1] Because of this sudden inflow to ESG investing, institutional investors have had to quickly integrate sustainable investments into their portfolios. However, as institutional investors typically vary in their mandates and skills, this has created heterogeneity across institutional investors.[2]

This paper documents the effects of skills and sentiment in sustainable investing. We show that the inflow to ESG investing has been lead by an increased sustainability sentiment. During this period, the investors with freer mandates act as skilled investors: They purchase stocks which tend to experience future ESG score increases. We see that these unconstrained investors capitalise on this, as they later sell their stocks to the constrained investors. Hence, the constrained investors' demand for sustainable investments leads to high returns for those stocks, which have realised a higher ESG score, leading to a positive ESG premium among stocks with high unconstrained ownership.

We show that this finding can be explained by a combination of heterogeneity in the skill of predicting ESG scores and an overall sentiment to invest sustainably, together leading to high returns from sustainable investing for the skilled investor.[3] To explain this formally, we introduce

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[1] The capital invested in ESG funds more than doubled in 2020 (Morningstar's 2020 Sustainable Funds Landscape Report). Additionally, new ESG investments of $51.1 billion make up nearly one fourth of the total inflows into U.S. funds. From 2002 until the end of 2017 the amount of assets incorporating ESG principles has risen from just under $ 2 to $ 10 trillion (Forum for Sustainable and Responsible Investment in the USA's 2018 Report).

[2] One might think that investors with a flexible mandate would not care to incorporate sustainable preferences into their investment strategy, but that is in fact not the case. For example, BlackRock has committed to take sustainability concerns into consideration to capture the opportunities presented by the net zero transition (BlackRock's letter to CEO's 2020).

Additionally, there is evidence that hedge funds short firms that they believe have bad ESG prospects and enter as activist investors, see Activist hedge funds prefer to fight ESG stars, Global Capital, 27th August 2020, and DesJardine and Durand (2020), DesJardine et al. (2020).

[3] Hartzmark and Sussman (2019) show that investors value sustainability and chase sustainable stocks. Investor sentiment for funds with high sustainability ratings resulted in net inflows of more than $ 24 billion, whereas

skill and sustainability sentiment to the standard Capital Asset Pricing Model. We do so by allowing skilled investors to be able to predict future ESG scores, an addition to the model of sustainable investments by Pástor et al. (2021).

Earlier sustainable investing models fall short in explaining our findings. For example, we see a negative general ESG premia, whose size varies with sustainability sentiment (as in Pástor et al., 2021), and that it can occasionally yield positive returns, as in Pedersen et al. (2020) where ESG serves as a hidden quality factor. However, neither theory can explain why only some investors yield positive abnormal returns from their ESG investments. In our model, we distinguish between two types of investors with heterogeneous skills and sustainability sentiment, where only one of them is able to predict future ESG score increases, leading to positive abnormal returns as the higher ESG score materialises due to the general sustainability sentiment.

To empirically tease out the effects of skill from a general ESG premium, we separate our investors into two groups.[4] We refer to the first group of investors as socially unconstrained investors, as they tend to be more unconstrained in their investment mandates (these include mutual funds, hedge funds, and other independent investment advisors). Correspondingly, the group of investors with stricter investment mandates is referred to as socially constrained (they include university endowments, pension plans, employee ownership plans, banks, and insurance companies).

We see that ESG investing has yielded negative excess returns on average. However, when separating our investors, we find that stocks with a high ESG score held by unconstrained investors have earned large positive returns over recent years. Interestingly, the premium does not exist among stocks with high constrained ownership. So despite that we see sustainable investing, on average, yields negative expected excess returns, a significant positive abnormal return can be achieved by investing sustainably in a smart way.

We go on to explore what may be driving the different returns to sustainable investing across the two groups. First, we consider whether there is a difference in the two investors' behavior. Specifically, we see how the investments' ESG scores develop after the purchase by either type. Here we find that unconstrained investor ownership predicts future ESG score increases, whereas constrained ownership does not. Additionally, the effect does not seem to be arising from a general skill of the unconstrained investor, as we only see abnormal returns amongst their ESG stocks, not stocks in general.[5]

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funds regarded as less sustainable experienced net outflows of $ 12 billion dollars, after Morningstar first published sustainability ratings in March 2016.

[4] We follow the seminal paper of Hong and Kacperczyk (2009), which means we consider institutional investors only and neglect retail investors. Any institutional investor belongs to one of the two groups.

[5] As we find the abnormal returns to be driven by stocks in the top quartile of ESG scores, it suggests that constrained investors may tend to follow a best-in-class mandate, such that when firms go from having a good to a

Second, we test whether predicting ESG scores carries a premium through a Fama MacBeth approach and run a regression of returns on changes in ESG scores whilst controlling for risk factors. In line with our hypothesis we find that predicting ESG scores carries a premium. This premium is 8 bp per month per score increase predicted, or 10 bp per standard deviation move in ESG score changes.

Third, we consider whether constrained investors indeed buy the unconstrained investors' stocks after their higher scores materialize. This purchase represents an opportunity that they potentially could not have exploited before due to their mandate. We test this by exploring whether constrained investors purchase high ESG stocks from constrained investors compared to other investors. In line with our expectation, we see that constrained investors have purchased an amount equal to about half of the outstanding high ESG shares from unconstrained investors relative to constrained investors since the financial crisis.

We continue by examining another channel of positive returns from sustainable investments, which is the role of sustainability sentiment. First, we construct a new measure of climate sentiment shocks from Google search volumes on the term *Climate change*.

We utilize our sentiment measure in our empirical analysis, and find that it follows recent inflows into ESG funds. The results show that as sustainability sentiment rises, it leads to positive abnormal returns for sustainable investments. As robustness we find quantifiably similar results for another sentiment measure by Engle et al. (2020). Additionally, we see that climate sentiment tends to be negatively correlated with economic sentiment as Baker and Wurgler (2006), making it a potential recessionary hedge. As sustainability sentiment theoretically should affect all high ESG stocks equally and independently of ownership, it is consistent with theory that we find our result to hold for sustainable investing among both unconstrained as well as constrained investors. This result shows that sustainability sentiment has experienced a strong increase over the last decade, and helps us understand returns to sustainable investing as well as the growth of the ESG investment industry at large.

Traditionally, finance has considered the returns to investing as being driven exclusively by risk.[6] More recent perspectives, however, additionally feature a more prominent role for returns to be driven by sentiment in the economy in general, and preferences of investors in particular. Influential papers establishing sentiment and preference explanations include Baker and Wurgler (2006) and Hong and Kacperczyk (2009). These papers show that sentiment plays a significant role in return dynamics during the transitional periods of the economy's business cycles, and that preferences play a key role in the cross-section of returns. This paper contributes to this discussion

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very good ESG score, the demand and return follow.

[6] As shown in the seminal paper by Sharpe (1964).

by separating out the transitory effects of changing sentiment from the generally expected return to sustainable investing. Hence, it offers an answer to the question of what the capital reallocation to ESG stocks means for the expected returns to sustainable investing.

This paper contributes to the literature as it documents heterogeneity in the returns to sustainable investing across investors, and uncovers that their skill in predicting ESG scores drives this difference. Therefore, it also helps explain why some find that sustainable investing leads to higher abnormal returns and some find that it lowers them.[7] Our answer is that it depends to which degree assets are held by which type of investor. Additionally, we show that the possible positive returns from sustainable investment in general is not necessarily contrary to theory, as it may be due to the increase in climate sentiment over the same period.[8]

Our study is the first to document the difference in sustainable investment returns across investor types.[9] These findings are important to the finance community, as they illustrate how sustainability restrictions on asset holdings have affected returns, which sustainable investing strategies pay off, and what implications they may have for expected returns within sustainable investing going forward.

The remainder of this paper is structured as follows. Section 2 exhibits our theoretical framework and defines our hypotheses to be tested in our empirical analysis. Section 3 describes our data. Section 4 documents our empirical analysis and findings. Section 5 concludes the paper.

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[7] Friede et al. (2015) conducts a meta study of over 2000 studies from 1970's to 2015 and find that a large majority of studies report a positive relationship between ESG and financial performance. And that over 90% report a non-negative relationship.

[8] Papers that investigate the relationship between social responsibility and stock performance include Dimson et al. (2015), Eccles et al. (2014), Fatemi et al. (2015), Ge and Liu (2015), Krüger (2015), Porter and Kramer (2006) who argue that there is a positive relationship between an increase in sustainability efforts and returns. Furthermore, Greening and Turban (2000), Porter and Van der Linde (1995), Xie (2014) argue that there are additional benefits as improved resource productivity, motivated employees, or more customer satisfaction (as cited in Fatemi et al., 2018). Others, on the other hand, argue that there is no causal relationship between returns and sustainabaility efforts (e.g. Alexander and Buchholz, 1978, Bauer et al., 2005, Hamilton et al., 1993, McWilliams and Siegel, 2000, Renneboog et al., 2008). Finally, there is also evidence for a negative causality as provided by, for example, Boyle et al. (1997), El Ghoul and Karoui (2017), Fisher-Vanden and Thorburn (2011)

[9] The closest paper to ours is Cao et al. (2019), which documents that high ESG firms are more prone to overpricing, and that this mispricing gets corrected to a lesser extend, leading high ESG firms to exhibit lower abnormal returns. We, on the other hand, find that high ESG stocks held to a large degree by socially unconstrained investors yield *high* abnormal returns, suggesting that the skill channel seems to be dominating the ESG sentiment channel. Cao et al. (2019) follow a different identification strategy through their revealed preference approach, whereas we separate investors into socially constrained and unconstrained as in Hong and Kacperczyk (2009). Our findings also differ from the seminal work by Hong and Kacperczyk (2009), as our main result originates in the top quartile of ESG scores rather than the bottom. Our results are furthermore robust to a within industries specification, rather than comparing 'Sin' industries to the rest. While we in general also see insignificant but negative returns for a general ESG strategy, our results also show that unconstrained investors manage to achieve positive abnormal returns for their ESG strategy, illustrating the importance of skill, and not just sustainability preferences. Thus, our results shed light on why it can be difficult to measure a negative ESG premia, as on the one hand, a sustainability premium drives expected returns downwards, whereas investor skill increases these very returns.

2 A Theory of Sustainable Asset Pricing with Skill

To guide our empirical approach and to gain an increased understanding of our results, we here describe the theoretical foundation of our study. We follow Pástor et al. (2021) and consider a general equilibrium economy with a continuum of agents who dislike risk and have heterogeneous preferences for ESG. We deviate from their setup by making some investors skilled in the sense that they have an above average ability to predict a stock's greenness score. Their approach deviates from the standard CAPM of Sharpe (1964) and Lintner (1965) by adding the sustainability preference. Specifically, the model is set in a single period, from time 0 to time 1, and the agent's utility is

$$U[W_{1i}, \boldsymbol{X}_i] = -e^{-aW_{1i} - b_i' \boldsymbol{X}_i}, \tag{1}$$

where the utility of investor i stems from their wealth at the end of period 1, W_{1i}, and is proportional to the absolute risk aversion a. The utility the investors get from holding sustainable stocks is proportional to the non-pecuniary benefits b_i. $\boldsymbol{X}_i$ is a vector of stock weights. $\boldsymbol{b}_i$ is a vector, which depends on the greenness $\boldsymbol{g}$ of the stock and the agent's individual sustainability preference d_i ($\boldsymbol{b}_i = d_i \boldsymbol{g}$).

The wealth evolves as $W_{1i} = W_{0i}(1 + r_f + \boldsymbol{X}_i' \boldsymbol{r}^e)$, where $\boldsymbol{r}^e$ are returns in excess of the risk-free rate r^f. The excess returns will be determined in equilibrium as

$$\boldsymbol{r}^e = \boldsymbol{\mu} + \boldsymbol{\epsilon}, \tag{2}$$

where $\boldsymbol{\mu}$ are expected returns and $\boldsymbol{\epsilon}$ captures the risk distributed as $N(\boldsymbol{0}, \boldsymbol{\Sigma})$.

This means that the investor's optimal weights will be

$$\boldsymbol{X}_i = \frac{1}{\gamma} \boldsymbol{\Sigma}^{-1} (\boldsymbol{\mu} + \frac{1}{\gamma} \boldsymbol{b}_i), \tag{3}$$

where $\gamma \equiv a_i W_{0i}$ is the relative risk aversion. Note that if $\boldsymbol{b}_i$ is a zero vector, we return to the standard result.

For the market to clear, the expected excess returns has to be

$$\boldsymbol{\mu} = \gamma \boldsymbol{\Sigma} \boldsymbol{x} - \frac{\bar{d}}{\gamma} \boldsymbol{g}, \tag{4}$$

where x is the supply of risky assets, $\bar{d}$ is the wealth-weighted average sustainability preference. Again, if $\bar{d}$ is zero, we obtain the original result. This can be written in terms of the market return as

$$\boldsymbol{\mu} = \mu_M \boldsymbol{\beta} - \frac{\bar{d}}{\gamma}\boldsymbol{g}, \tag{5}$$

where $\boldsymbol{\beta}$ are the market betas $(1/\sigma_M^2)\boldsymbol{\Sigma x}$. Finally, this means that the alpha of a stock n will be

$$\alpha_n = -\frac{\bar{d}}{\gamma} g_n. \tag{6}$$

For our empirical work we use Equation (5) to rewrite Equation (2) to the testable form for a stock

$$r_n^e = \underbrace{-\frac{\bar{d}}{\gamma} g_n}_{\alpha_n} + \mu_M \beta_n + \epsilon_n. \tag{H1}$$

By combining Equation (3) and (5), and noting δ_i as the preference deviation from the mean $(d_i - \bar{d})$, we can see the equilibrium portfolio weights must be

$$\boldsymbol{X}_i = \boldsymbol{x} + \frac{\delta_i}{\gamma^2}(\boldsymbol{\Sigma}^{-1}\boldsymbol{g}). \tag{7}$$

It is interesting to note that this implies three-fund separation, as this can be achieved for each agent using the risk-free asset, the market portfolio $\boldsymbol{x}$ and an ESG portfolio, the last term above. Hence, the second term illustrates investors' ESG tilt. If all investors had the same preference, δ_i would be zero, and no investor would have an ESG tilt. Everyone holds the market portfolio and there is no reason for advisors to offer ESG products to their investors.

It is further interesting to note that as risk aversion increases, the portfolio tilt decreases, as investors start worrying more about risk than sustainability relative to before.

However, returns could also be affected by changes to green sentiment. These changes can arise from unexpected changes in the average investor preference or the end consumers' taste for green goods. These two changes will lead to lower future expected return, and positive unexpected realized returns of

$$\boldsymbol{r}^u = s_g \boldsymbol{g} + \boldsymbol{\epsilon}, \tag{8}$$

where s_g is sentiment. Additionally, sentiment is the combination of the two random preference shocks

$$s_g = z_g + \frac{1}{\gamma}(\bar{d}_1 - E_0[\bar{d}_1]), \tag{9}$$

where z_g is the consumer taste shock. We hence note that sentiment shocks, which is also the unexpected ESG factor return, can arise from consumer or investor preference changes, which we jointly refer to as sentiment shocks. Additionally, we will for simplicity treat sentiment shocks as the investor channel in this paper, even though they could be customer shocks. This choice has no impact on our results later in the paper.

The total excess return of a stock can then be closely approximated by

$$r_n^e = \beta_{M,n} r_M^e + g_n(s_g + \mu_g) + \epsilon_n, \tag{H3}$$

where $E_0[\epsilon_n] = 0$ and μ_g is the expected return on the ESG portfolio $\mu_M \beta_g - \bar{d}/\gamma$. Here, β_g is the ESG portfolios beta with the market portfolio, making the ESG factor's realized return $s_g + \mu_g$ and $E_0[s_g + \mu_g] = \mu_g$.[10] Hence, Equation (9) illustrates how increased sentiment (changes in ESG preferences) enters into the excess returns of Equation (H3), and boosts the returns of green stocks. Another interesting note is that stocks will now have zero alpha when regressed against the market excess return and the ESG portfolio return.

Skill in sustainable investing with sentiment. Our addition to Pástor et al. (2021) is that we consider the case where a small fraction of skilled investors is able to predict future ESG scores, for example through analyses of firm fundamentals and strategy. The shock to the greenness of firm n of $\tilde{g_n}$ leads to a new total excess return for a stock of

$$r_n^e = \beta_{M,n} r_M^e + g_n \mu_g + \tilde{g}_n \frac{\bar{d}}{\gamma} + \epsilon, \tag{H2}$$

and hence effectively boosts the return of the skilled investor.

In the empirical work that follows, we test three hypotheses. Our first hypothesis is whether investors have a sustainability preference. Specifically, we test that the wealth-weighted average sustainability preference is positive, so that $\bar{d} > 0$. A positive sustainability preference implies that green stocks have a negative alpha, as according to Equation (H1). This also implies that an ESG factor has negative alpha. We test this against the null-hypothesis that investors sustainability preference is zero, which means that the alphas are also zero.

Our second hypothesis is that some investors are able to predict future ESG score changes $\tilde{\boldsymbol{g}}$, which means they can achieve a positive alpha in their investments into green stocks, as according to Equation (H2). This is tested against the null that $\tilde{g}_g = \mu_g = 0$, which is a stronger test than $\mu_g < 0$, as the latter is easier to reject. One could also use a one-sided test, as there is no reason to expect a negative sustainability preference, and we just want to see if it is significantly larger than zero.

Our final hypothesis is whether an increased worry of climate change, as well as a tenfold

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[10] β_g can be negative either if the covariance with the fundamental risk is negative or if the stock market is value-weighted brown. From our empirical analysis, our negative β_g seems to be explained by the ESG-factor doing well in bad times, implying a negative correlation with fundamental payoff risk.

increase in assets with an ESG mandate, over the last fifteen years has lead to positive unexpected return for green stocks, an effect which we will refer to as *Sentiment*. The expected return is then governed by Equation (H3), which we test against the null that $f_g = \mu_g = 0$, which, again, is a stronger test than $\mu_g < 0$ as our hypothesis is that $f_g > 0$.

3 Data

This section outlines the data sources and places them within our analysis.

Returns. The objective of the analysis requires us to combine data on equity returns and sustainability. First, we obtain monthly stock returns from the Center for Research in Security Prices (CRSP). We also obatin monthly data points on the number of stocks and their share price to compute market values. We follow Fama and French (1993) and only include stocks that are listed on NYSE, AMEX, or NASDAQ and have a CRSP share code of 10 or 11.

ESG. We utilize a unique ESG dataset to tackle our research question. Specifically, we download yearly ESG score data from Thomson Reuters, referred to as ASSET4. This data depicts equally-weighted ratings on the metrics of companies' economic, environmental, social and corporate governance performance. In particular, the ESG score is a measure from 0 to 100. A low score suggests that a given company behaves poorly with regards to overall sustainability, and vice versa. The higher a company's score, the more sustainable it is with regards to the pillars mentioned above.

There are important facts to consider on these ESG scores. The ASSET4 database experienced an update of scores in the year of 2020, however, we use scores downloaded in 2018.[11] These 'original' scores, as Berg et al. (2020) put it, have not been backfilled, meaning that there would not be an assignment of scores for any other than the most recent year. For example, if Thomson Reuters did not assign a score for the year 2005 due to insufficient information but then receives valuable insights in 2008 for the year of 2005, they would not go back in time and assign a score for the year of 2005.[12] This is important because our analysis makes the implicit assumption that investors had the relevant ESG score information for the previous year available at the time. Furthermore, Berg et al. (2020) point out that the update of scores in 2020 is systematic and related to past performance. It seems as if firms that have outperformed others in a given year have received higher ex-ante scores in the update. The updated data would therefore distort our results and it is hence important for us to use the 'original' data instead as we analyze the skill to

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[11] Other studies having used the same data include, for example, Breuer et al. (2018), Dyck et al. (2019), Stellner et al. (2015).

[12] We gathered this information from an interview with the persons responsible for the ESG data bank at Thomson Reuters.

invest sustainably with information at the time. Finally, although Berg et al. (2019) find that the ASSET4 data is not perfectly correlated with other widely used sustainability assessment data, it still displays a strong positive correlation. For example, the correlation between ASSET4 and Sustainalytics and Vigeo Eiris is 0.67 and 0.69, respectively, equating to an R^2 of 81% and 83%. The availability of scores to investors at the time, high correlations to other data providers, and a long time horizon are the deciding factors for us to use the ASSET4 database in our study.

Thomson Reuters computes the scores themselves and follows a strict methodology when doing so. For every firm, they consider a total of 750 questions, which they attempt to gather information for. Data are collected from multiple sources, including: a) company reports; b) company filings; c) company websites; d) NGO websites; e) CSR Reports; and f) reputable media outlets. Thomson Reuters writes that every data point goes through a multi-step verification process, including a series of data entry checks, automated quality rules, and historical comparisons. These data points reflect more than 280 key performance indicators and are rated as both a normalized score (0 to 100, with 50 as the industry mean) and the actual computed value. The equally-weighted average is normalized by ASSET4 so that each firm is given a score relative to the performance of all firms in the same industry around the world; in other words, the ratings are industry-benchmarked.[13]

We merge the return data from CRSP with the ESG data according to their CUSIP codes. ESG data points are available on a yearly basis, whereas returns are available at a monthly frequency. This means that the individual firm's ESG score is the same throughout a given year, i.e. for every monthly return observation. ESG scores are available from 2002 until 2016, which defines our sample period. This is a longer time period than most other data providers can offer, which additionally encourages us to use the ASSET4 scores.[14]

Investigating the ESG data set in greater detail, Table 1 shows distribution statistics and developments in ESG scores over time. In the first year of the sample period, 2002, a total number of 624 firms in the sample were assigned an ESG score. This number significantly increases to a maximum of 2,992 firms in the final year of 2016. The distribution of ESG scores over time remains relatively stable. We see scores on both the low and the high end of the scale.

For the empirical analysis in the next section, the entire universe of ESG score firms are taken into account. The total number of firms is thereby identical to the number of firms in Table 1. This also implies that the cross-section's total number of firms in later performance analysis rises over time.

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[13] The interested reader can find a more detailed description on how Thomson Reuters determines their ESG scores at `http://www.esade.edu/itemsweb/biblioteca/bbdd/inbbdd/archivos/Thomson_Reuters_ESG_Scores.pdf`.

[14] The MSCI KLD data is available for a slightly longer time horizon, however, their dataset experienced significant updates in between. These updates violate our binding constraint that investors need to be ensured to have had access to the very scores we use in our analysis.

Table 1: ESG data availability

The table covers the descriptive statistics of the ESG data set used in the analysis. The minimum, quartiles, maximum and standard deviation (equally-weighted) are computed over all companies exhibiting an ESG score for a given year.

Year	# of firms	Min	1. Quartile	Median	Mean	3. Quartile	Max	Std
2002	624	3.260	20.688	41.265	48.168	78.302	98.720	30.722
2003	629	3.800	20.570	42.950	48.663	78.390	98.680	30.364
2004	903	3.740	29.555	54.180	55.151	82.865	98.380	28.482
2005	1,029	4.660	31.590	55.590	57.137	85.860	98.490	28.661
2006	1,030	4.250	31.675	55.045	56.947	85.222	98.250	28.373
2007	1,075	3.880	31.140	57.640	57.548	86.170	97.300	28.326
2008	1,327	3.570	26.680	53.320	54.599	85.345	97.500	29.536
2009	1,469	2.960	27.290	51.920	54.572	85.110	97.460	29.660
2010	1,541	3.580	29.810	55.250	56.883	86.900	97.100	28.884
2011	1,522	3.920	28.395	58.545	57.055	86.980	96.600	29.353
2012	1,534	2.970	27.055	56.760	55.713	86.490	96.800	29.745
2013	1,521	2.970	29.210	57.800	57.057	87.150	96.950	29.386
2014	1,527	3.000	31.575	59.910	57.757	86.515	97.110	28.938
2015	2,225	4.320	14.940	45.590	48.525	82.740	96.590	32.527
2016	2,992	4.830	15.360	28.050	43.897	79.983	96.430	32.300

Risk factors. To control for risk factors we use the risk-free rate and factor-returns of the Fama and French (1993) three-factor model as well as the momentum factor from Ken French's website. We test our hypotheses against the CAPM, Fama-French three-factor model and Carhart four-factor model.

Business cycles. We use the NBER Business Cycle Reference Dates to identify recessions and use these to define good and bad economic times. We use these bad times as a proxy to investigate how ESG returns perform during periods of high risk and low consumption. In a later analysis, we further utilize price-dividend ratios (PD) as a measure for the state of the stock market. The PD data is gathered from Shiller's website.

Ownership. We obtain quarterly institutional holding data (13F) from Thomson Reuters. According to the SEC, all institutional investors with assets under management over $100 million need to report their holdings to the commission.[15] Specifically, we use the data in a way that it shows us information on institutional ownership as percentage of a firm.

The data includes the number of shares held by every institutional investor. We use this number to calculate the relative holding of a firm by each institutional investor. Specifically, each investors' number of shares divided by the total number of shares outstanding depicts the holdings of a given

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[15] A short overview of the SEC's regulatory requirements is found at `https://www.sec.gov/fast-answers/answers-form13fhtm.html`. It generally defines which type of investor is categorized as institutional and what rules they are ought to follow.

firm. Sometimes, the data does not adjust for stock splits or repurchases and the relative share might increase above one, in which case we exclude it from the data. We further follow standard asset pricing literature and exclude stale data, whenever there are several filing dates ($fdate$) for the same report date ($rdate$). In such a case, we only keep the data points of the report date with the earliest filing date.[16]

The institutional ownership data (13F) exhibits five different types of owners which we categorize into socially constrained and unconstrained investors as in Hong and Kacperczyk (2009). Socially constrained owners are banks (Type 1), insurance companies (Type 2) as well as all other other institutions, which includes universities, pension plans, and employee ownership plans (Type 5). Socially unconstrained owners are mutual funds (Type 3) and independent investment advisors (Type 4), which also includes hedge funds. We aggregate holding data for these two groups and merge it with returns.

Sentiment. We test for sentiment by using the search interest of 'Climate change' on Google Trends. Figure 1 shows how our sentiment time series is constructed. The general hits measure is the search volume in the United States expressed relative to the maximum search volume in percent (top left). As it is clearly seasonally affected, we show the difference to the same month a year ago in the top right panel. The bottom left panel shows the innovations from fitting an AR(1) model on the seasonally adjusted hits, which serves as our sentiment measure. The bottom right shows the cumulated hit innovations. The shaded area denotes the recession. We notice a general fall in sentiment in the recession, a sharp peak between the recession and the European debt crisis, and a steep rise since 2014.

We further use measures such as the Baker and Wurgler (2006) sentiment measure, which is the principal component of five sentiment proxies ($perp$). Finally, we utilize the (Engle et al., 2020) text-based climate measure, which is based on text coverage of *Climate* in the Wall Street Journal. They have two measures. One for general coverage (wsj) and one for negative coverage ($chneg$).

One might be concerned that our measure is overly simplistic or that climate deniers account for a significant fraction of the time series' movements. We argue that climate deniers only represent a negligible fraction of the population and that their search intensity is relatively constant over time, whereas the worry of climate change has varied over the last decades with an overall rising trend. Hence, by using the variation of search volumes, we believe to capture climate change worries to a large degree. Additionally, robustness tests with the more complicated text-based sentiment measure by (Engle et al., 2020), constructed from a high-dimensional dataset, show qualitatively

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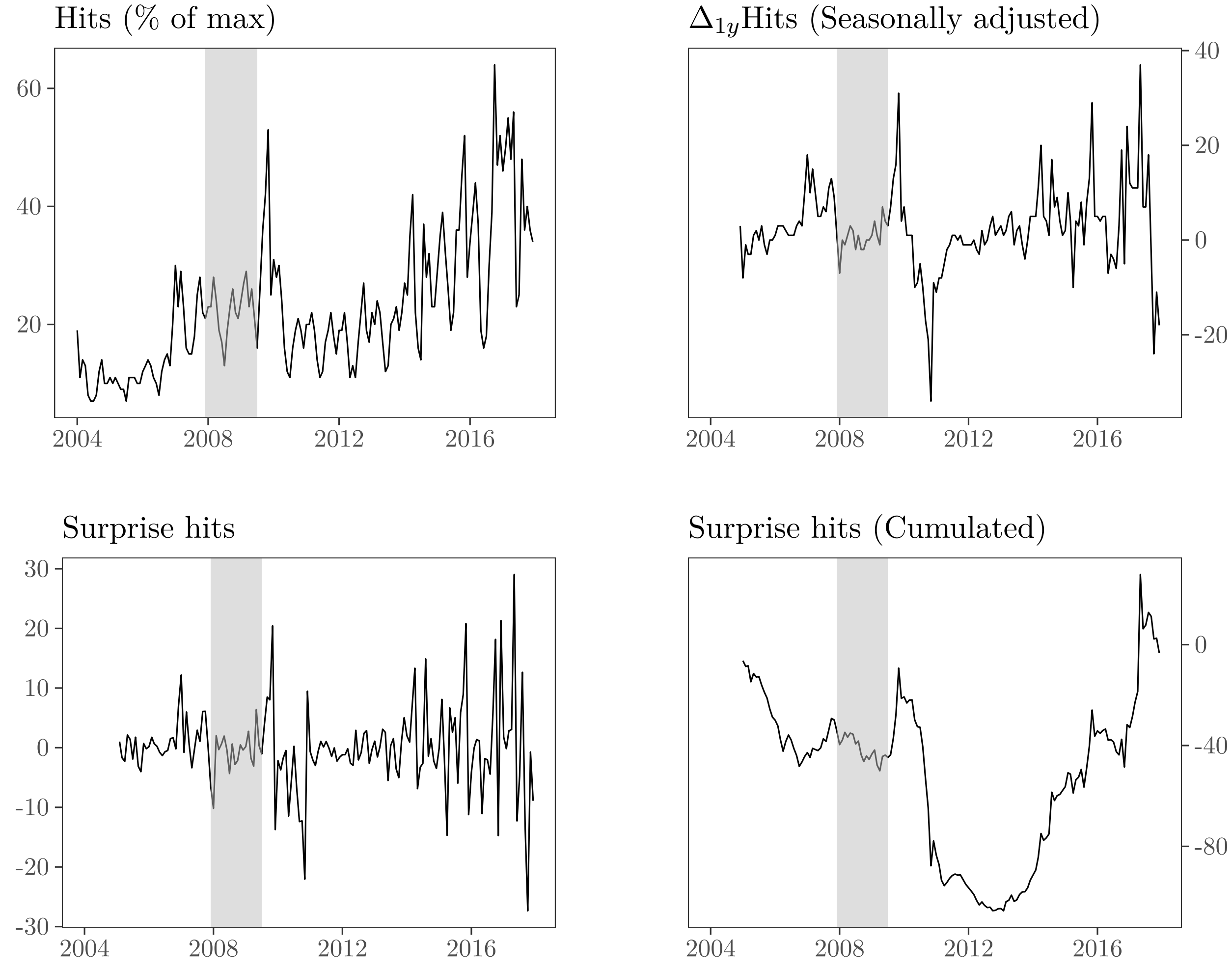
[16] For similar applications, see, for example, Brunnermeier and Nagel (2004) or Blume et al. (2017).

similar results. Therefore, we see the simplicity and transparency of our measure as a virtue.

Figure 1: Climate sentiment

We show how our sentiment measure is constructed. The top left panel shows the monthly Google searches for *Climate change*. As it is clearly seasonally affected, we show the difference to the same month a year ago in the top right panel. The bottom left panel shows the innovations from fitting an AR(1) model on the seasonally adjusted hits. The bottom right shows the cumulated hit innovations. The shaded area denotes the recession.



4 Results

We empirically investigate the relationship between ESG scores and equity returns. Specifically, we test three hypotheses we developed in Section 2. That is, we test the relationship of a stock's greenness and its expected return for two types of investors (Equation H1), whether investors are compensated for predicting ESG scores (Equation H2), and finally whether climate sentiment has increased abnormal returns of green stocks (Equation H3).

4.1 Returns to sustainable investing across investor types

In this subsection, we compare the returns to sustainable investing for two types of investors (Equation H1 in Section 2). Specifically, we consider the ESG premium earned by socially constrained and unconstrained investors.

We construct our results by first sorting returns according to lagged ESG scores in a total of four portfolios.[17] In the next step, we conditionally sort returns according to their previous quarter's socially unconstrained and constrained institutional ownership share and assign them into another four portfolios. This gives us a total of 16 portfolios. We value-weight these portfolios and risk-adjust returns according to the the Carhart four-factor model.

We show the sustainable investing results, the estimation of Equation H1, in Table 2. Comparing unconstrained investors in Panel A and constrained investors in Panel C, we find that unconstrained investors earn a significant ESG premium of 30 bp a month, whereas constrained investors do not earn a significant abnormal return across ESG firms.[18] This result is driven by the high returns in the long leg. The long leg, which is the high ESG and high unconstrained ownership portfolio, earns an abnormal return of around 40 bp. These results demonstrate an important difference in the outcome from sustainable investing by socially unconstrained and constrained investors, that is, unconstrained investors demonstrate skill in sustainable investing. Unconstrained investors are able to invest in high ESG firms whilst earning high returns. We explore a key driver of this skill in the next chapter.

Table 2's Panels B and D depict our second test. Here, we examine the performance of stocks as they are bought by socially unconstrained and constrained investors. We do this by considering the next period holdings. For example, if an investor held 10% of Stock A in Q2 2015, we run the regressions as if that investor held 10% of Stock A in Q1 2015 (which we refer to as *sorted on future holdings*). This gives us a way to consider the performance of stocks that the two investor types demand. We follow our double-sort methodology and sort stocks on ESG scores as well as future holdings. We risk-adjust abnormal returns of the 16 normal portfolios as well as the four long-short portfolios, and document the results in Panel B and Panel D.

Results from our second test show that high ESG stocks held by both investor types in the next quarter yield a positive and significant abnormal return. Unconstrained investors earn 42 bp per month and constrained investors earn 33 bp per month. However, it is not significant for other

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[17] We form portfolios in the standard way of Fama and French (1992). More details on sorting can be found in Appendix B.

[18] Table C.2 in Appendix C.2 shows additional results for unconstrained investors.

Table 2: Returns to sustainable investing across investor types and timings

We first sort returns according to lagged ESG scores in a total of four portfolios. In a next step, we conditionally sort returns according to their previous quarter's socially unconstrained and constrained institutional ownership share and assign them into another four portfolios, ending up with a total of 16 portfolios each. We conduct this procedure on actual holdings at time t (*sorted on actual holdings*), and also at time $t + 1$ (*sorted on future holdings*), which gives us an indication for what the return on these portfolios would have been if investors would have held firms to the same level a period earlier. Here, one period equates to three quarters as holding data is available on a quarterly basis. LS is the abnormal return from a long-short strategy which goes long in high ESG and short in low ESG firms, giving us another four portfolios each. We value-weight and risk-adjust returns according to the Carhart four-factor model. We display alphas as well as relevant t-test statistics. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months. Bold numbers represent statistical significance at a level of 5% or below.

	Sorted on actual holdings					*Sorted on future holdings*				
	ESG low	Q2	Q3	ESG high	LS	ESG low	Q2	Q3	ESG high	LS
	Sorted on Socially Unconstrained Ownership Holdings									
	Panel A					*Panel B*				
Low	0.021	-0.064	-0.03	0.169	0.148	-0.118	-0.263	-0.194	-0.032	0.086
t-stat	0.123	-0.54	-0.177	1.278	0.565	-0.597	-1.612	-1.153	-0.253	0.313
2	0.046	0.065	-0.151	0.019	-0.027	-0.218	0.054	-0.039	0.071	0.289
t-stat	0.347	0.506	-1.067	0.21	-0.13	-1.59	0.381	-0.291	0.861	1.453
3	-0.033	-0.017	0.024	0.007	0.041	0.259	0.24	0.107	0.125	-0.134
t-stat	-0.228	-0.121	0.191	0.057	0.217	2.067	1.867	1.038	1.427	-0.841
High	0.088	0.005	0.173	**0.392**	**0.304**	0.132	-0.008	0.121	**0.419**	0.288
t-stat	0.773	0.041	1.202	3.784	2.027	0.975	-0.065	0.824	5.551	1.743
	Sorted on Socially Constrained Ownership Holdings									
	Panel C					*Panel D*				
Low	-0.124	0.071	-0.024	0.149	0.273	-0.165	-0.038	-0.183	0.072	0.237
t-stat	-0.672	0.439	-0.174	1.258	1.027	-0.854	-0.236	-1.047	0.599	0.869
2	0.207	0.188	0.094	0.077	-0.129	0.193	0.073	0.193	0.108	-0.084
t-stat	2.720	2.051	0.841	0.933	-1.218	1.788	0.599	1.271	1.337	-0.689
3	0.054	0.038	-0.053	0.074	0.020	0.045	0.179	0.032	0.102	0.057
t-stat	0.296	0.33	-0.436	0.644	0.106	0.279	1.528	0.248	1.207	0.302
High	-0.049	-0.324	-0.190	0.130	0.179	-0.018	-0.171	-0.036	**0.325**	0.344
t-stat	-0.374	-1.765	-1.141	1.108	1.089	-0.145	-0.762	-0.205	2.232	1.661

ESG quartiles. This shows that ESG demand pushes up the price for ESG stocks. This suggests that there has been a larger increase in ESG demand than for the other stocks, or that the price elasticity is lower. In either case, this ESG demand leads, ceteris peribus, to lower ESG premia in the future. However, since we have seen a difference between the two types of investors in their returns to sustainable investing using actual holdings, it suggests that constrained investors have additional skill within ESG investing, which we will explore further in Subsection 4.2.

In a third test, we do not consider ownership and evaluate the general ESG premium. We create the ESG premium from a long-short portfolio, which goes long in the top decile ESG firms and shorts the lowest decile of ESG firms. Table 3 shows the results.

Table 3: Returns to sustainable investing in general

We construct equally- and value-weighted decile portfolios based on previous year ESG scores and adjust them in the beginning of each calender year. P1 (P10) depicts the low (high) ESG score portfolio. LS is a time series of returns that goes long in high ESG firms (P10) and shorts low ESG firms (P1). Returns are risk-adjusted through the application of the CAPM, Fama-French 3-factor, Carhart, and Fama-French 5-factor models and we report the alphas. We further document monthly excess returns, volatility and Sharpe ratio estimates. $t-values$ test if the estimated returns are significantly different from zero and bold numbers signal significance at the 10% level or less. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months.

Panel A: Equally-weighted

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	LS
Excess Return	**1.396**	**1.055**	**1.202**	**1.049**	**0.988**	**1.008**	**1.093**	**1.281**	**1.155**	**0.932**	**-0.123**
t-value	3.084	2.554	2.797	2.761	2.656	2.63	2.823	3.288	3.512	3.104	3.811
CAPM alpha	0.245	-0.011	0.097	0.061	0.017	-0.002	0.072	**0.257**	**0.276**	**0.12**	0.13
t-value	1.358	-0.086	0.753	0.565	0.099	-0.017	0.555	1.954	2.756	1.862	1.047
3-factor alpha	**0.257**	-0.008	0.108	0.064	0.023	-0.001	0.084	**0.267**	**0.29**	**0.118**	0.127
t-value	1.696	-0.083	1.007	0.661	0.177	-0.005	0.921	2.33	3.195	1.868	1.138
4-factor alpha	0.324	0.022	**0.169**	0.103	0.052	0.035	0.124	**0.313**	**0.309**	**0.139**	0.117
t-value	2.524	0.198	1.925	1.203	0.43	0.328	1.53	3.037	3.423	2.312	1.005
5-factor alpha	**0.363**	0.08	0.141	0.095	-0.004	-0.001	0.066	**0.205**	**0.247**	0.069	-0.011
t-value	2.592	0.843	1.404	1.047	-0.034	-0.008	0.744	1.957	2.711	1.109	-0.102
Volatility	6.064	5.537	5.754	5.089	4.981	5.134	5.187	5.222	4.403	4.023	2.474
Sharpe Ratio	0.23	0.191	0.209	0.206	0.198	0.196	0.211	0.245	0.262	0.232	-0.05

Panel B: Value-weighted

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	LS
Excess Return	**1.047**	**0.712**	**0.886**	**0.973**	**0.792**	**0.908**	**0.921**	**0.87**	**0.747**	**0.705**	**-0.343**
t-value	2.997	2.084	2.516	2.855	2.463	2.674	2.676	2.738	2.536	2.736	2.868
CAPM alpha	0.17	-0.171	-0.034	0.092	-0.043	0.02	0.012	0.028	-0.031	0.022	-0.148
t-value	0.972	-1.407	-0.274	0.987	-0.313	0.196	0.132	0.355	-0.412	0.341	-0.75
3-factor alpha	0.161	-0.188	-0.041	0.085	-0.043	0.009	0.017	0.038	-0.018	0.029	-0.133
t-value	0.916	-1.451	-0.277	0.887	-0.327	0.097	0.185	0.493	-0.245	0.419	-0.654
4-factor alpha	0.193	**-0.205**	-0.039	0.098	-0.041	0.025	0.039	0.035	-0.027	0.028	-0.166
t-value	1.129	-1.718	-0.264	1.015	-0.324	0.271	0.426	0.454	-0.367	0.414	-0.807
5-factor alpha	0.308	-0.132	-0.014	0.091	-0.095	0.08	0.032	0.015	-0.056	-0.023	-0.331
t-value	1.635	-1.004	-0.099	0.841	-0.685	0.779	0.378	0.197	-0.8	-0.364	-1.556
Volatility	4.675	4.584	4.716	4.56	4.298	4.543	4.607	4.257	3.945	3.45	2.712
Sharpe Ratio	0.224	0.155	0.188	0.213	0.184	0.2	0.2	0.204	0.189	0.204	-0.126

We see that there does not seem to be a general ESG premium after adjusting for risk, which confirms the findings by Berg et al. (2020). We find partial evidence that the firms in the lowest decile portfolio earn a positive abnormal return. We further find similar results for the highest decile portfolio of ESG firms in the equally-weighted case (Panel A). However, the value-weighted returns reject this observation. This suggests that this finding to be driven by small firms, and that there is neither a benefit nor a cost of investing sustainably in general, when not incorporating additional information.

We document robustness results of the long-short equity strategy by unconstrained investors for alternative risk models in Table 4.

Table 4: Robustness test of ESG premium for different degrees of socially unconstrained ownership across different models and ownership levels

We first sort returns according to lagged ESG scores in a total of four portfolios. In a next step, we conditionally sort returns according to their previous quarter's socially unconstrained institutional ownership share and assign them into another four portfolios, ending up with a total of 16 value-weighted portfolios. We construct long-short portfolios that go long in high ESG firms and short in low ESG firms with either a high (H) or a low (L) level of socially unconstrained ownership in $D = \{H, L\}$. We risk-adjust our long-short portfolio returns with the CAPM, 3-Factor as well as the Carhart four-factor model. We adjust standard errors according to Newey and West (1987) with a lag of 12 months and report relevant coefficients and t-values.

	Dependent variable:					
	ESG Long-short return for high or low degree of ownership, LS_t^D, $D = \{H, L\}$:					
	LS_t^H			LS_t^L		
	(1)	(2)	(3)	(4)	(5)	(6)
α	0.321^{**}	0.331^{**}	0.304^{**}	0.161	0.169	0.148
	t = 2.211	t = 2.199	t = 2.027	t = 0.704	t = 0.672	t = 0.565
mkt-rf	-0.169^{***}	-0.055	-0.019	-0.212^{***}	-0.148	-0.120
	t = -3.985	t = -1.295	t = -0.355	t = -2.673	t = -1.456	t = -1.126
smb		-0.491^{***}	-0.502^{***}		-0.295^{***}	-0.304^{***}
		t = -3.763	t = -4.002		t = -3.271	t = -3.207
hml		0.054	0.119		0.060	0.112
		t = 0.667	t = 1.446		t = 0.590	t = 1.161
mom			0.113^{**}			0.091
			t = 2.492			t = 1.274
Observations	180	180	180	180	180	180
R^2	0.058	0.200	0.226	0.087	0.135	0.151
Note:						*p<0.1; **p<0.05; ***p<0.01

In Columns 1 to 3, we confirm the results for all factor models. We further see that the premium partially loads on the market developments themselves and the small minus big factor. We do not see an ESG premium amongst stocks with low degrees of socially unconstrained ownership, see Columns 4 to 6. However, the ESG long-short strategy also significantly loads on the market and the small minus big factor. We further note that the long-short ESG factor loads on the momentum factor regardless of the ownership type. This fact serves as motivation for us to explore whether less risk-based factors may be driving these returns as, for example, sentiment.

We conduct two additional robustness tests as part of the this section's analysis. Specifically, we show results for other sustainability metrics. We download scores from Sustainalytics, another ESG data provider, as well as data points on firms' CO2 emissions per dollar of revenue. Data on firm-level CO2 emission is used by both ASSET4 and Sustainalytics as part of their scoring approach. Table 5 shows the results for portfolios under high unconstrained ownership and high scores under the alternative metrics (for CO2 per revenue, the 'sustainable' portfolio is that of firms with lowest emissions).

We see that our results are robust under the application of these different sustainability metrics. Firms with high socially unconstrained ownership and high sustainability scores (or low emission) pay high returns.We further show results under the application of different factor models in Table D.1 of Appendix D.

In the final robustness test, we create a our long-short portfolio under high socially unconstrained ownership and high sustainability scores according to the alternative metrics. Table 6 shows the results. We observe a significant sustainability premium under the Sustainalytics Environment (S:E) and the CO2 scoring models. For the general Sustainalytics scores, we document positive abnormal returns, though not at a significant level under the Carhart four-factor model.[19] These results suggest that the ESG premia for socially unconstrained investment strategies is driven by environmentally-related scores.

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[19] This premium is significant with a p-value of below 5% under the CAPM and the Fama-French 3-factor model.

Table 5: Robustness test for returns to sustainable investing for unconstrained investors using other sustainability metrics

We sort returns according to lagged scores in a total of four portfolios based on ASSET4 (A4), Sustainalytics (S), Sustainalytics Environment (S:E) and Carbon per Revenue (CO2) scores. Data goes from 2002 until 2016 under ASSET4 and 2011 until 2016 otherwise. In a next step, we conditionally sort returns according to their previous quarter's socially unconstrained institutional ownership share and assign them into another four portfolios, ending up with a total of 16 value-weighted portfolios. In another step, we construct value-weighted and risk-adjusted returns according to the Carhart four-factor model for the portfolio that goes long in high score (low score for CO2 metric) firms with high socially unconstrained ownership. We adjust standard errors according to Newey and West (1987) with a lag of 12 months and report relevant coefficients and t-values.

	Dependent variable:			
	A4	S	S:E	CO2
	(1)	(2)	(3)	(4)
α	0.392^{***}	0.384^{***}	0.372^{***}	0.585^{***}
	$t = 3.784$	$t = 4.579$	$t = 3.051$	$t = 4.080$
mkt-rf	0.987^{***}	0.963^{***}	0.988^{***}	1.046^{***}
	$t = 39.925$	$t = 13.709$	$t = 13.789$	$t = 16.699$
smb	-0.042	0.134^{**}	0.150^{**}	0.088
	$t = -0.594$	$t = 2.113$	$t = 2.296$	$t = 0.763$
hml	-0.091^{*}	-0.177^{***}	-0.271^{***}	-0.427^{***}
	$t = -1.690$	$t = -2.775$	$t = -4.350$	$t = -3.057$
mom	-0.001	0.023	0.029	-0.042
	$t = -0.039$	$t = 0.357$	$t = 0.456$	$t = -0.647$
Observations	180	72	72	72
R^2	0.877	0.816	0.797	0.732
Note:				$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table 6: Robustness test for sustainability premium under unconstrained ownership using other sustainability metrics

We sort returns according to lagged scores in a total of four portfolios based on ASSET4 (A4), Sustainalytics (S), Sustainalytics Environment (S:E), Sustainalytics Social (S:S), Sustainalytics Government (S:G) and Carbon per Revenue (CO2) scores. Data goes from 2002 until 2016 under ASSET4 and 2011 until 2016 otherwise. In the next step, we conditionally sort returns according to their previous quarter's socially unconstrained institutional ownership share and assign them into another four portfolios, ending up with a total of 16 portfolios. In a final, step we construct value-weighted and risk-adjusted returns under the Carhart four-factor model for a portfolio that goes long in high score firms and short in low score firms with high socially unconstrained ownership; in the case of CO2, we go long in low emission firms and short in high emission firms both with high socially unconstrained ownership. We adjust standard errors according to Newey and West (1987) with a lag of 12 months and report relevant coefficients and t-values.

	Dependent variable:					
	A4	S	S:E	S:S	S:G	CO2
	(1)	(2)	(3)	(4)	(5)	(6)
α	0.304**	0.226	0.393***	0.160	0.034	0.681**
	t = 2.027	t = 1.414	t = 2.811	t = 0.531	t = 0.155	t = 1.970
mkt-rf	−0.019	−0.055	−0.039	−0.016	−0.071	0.159
	t = −0.355	t = −0.871	t = −0.964	t = −0.133	t = −0.963	t = 0.867
smb	−0.502***	−0.021	−0.034	0.103	−0.139*	−0.048
	t = −4.002	t = −0.256	t = −0.452	t = 0.692	t = −1.701	t = −0.326
hml	0.119	0.255***	−0.011	0.238	0.273***	−0.552***
	t = 1.446	t = 4.023	t = −0.157	t = 1.540	t = 3.215	t = −2.916
mom	0.113**	0.144**	0.022	−0.094	0.018	0.137
	t = 2.492	t = 2.277	t = 0.265	t = −0.855	t = 0.263	t = 1.324
Observations	180	72	72	72	72	72
R^2	0.226	0.092	0.012	0.088	0.106	0.193

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

4.2 Skills in sustainable investing across investor types

We give an explanation as to where socially unconstrained investors' abnormal returns from sustainable investing come from. Specifically, we test our second hypothesis, stating that investors are compensated for predicting ESG scores (Equation H2 in Section 2).

ESG score changes across investor types' holdings

The first step is to see whether unconstrained investors are better at predicting changes in firms' ESG scores. We test this by estimating

$$\Delta ESG_{i,t,t+N} = \alpha + \beta^I O^I_{i,t} + \epsilon_{i,t}, \tag{10}$$

where $\Delta ESG_{i,t,t+N}$ is the cumulative ESG score difference between the lagged ESG score in year t and $t+N$ years ahead. The variable $O^I_{i,t}$ is the relative institutional ownership of firm i at time t held by socially unconstrained or constrained investors $I = \{U, C\}$. Additionally, we allow for heteroskedastic standard errors and control for industry-year effects. Figure 2 presents the results.

Figure 2: Predicting ESG score changes

Figure 2a shows socially unconstrained (U) ownership in firms and their correlation to future changes in ESG scores, whereas Figure 2b shows this effect for socially constrained (C) investors. Specifically, the β-estimate gives an indication for how much the ESG score changes in N years ahead of time, when investor $I = \{U, C\}$ increases ownership by one percent today. Allowing for heteroskedasticity, the gray shade shows White standard errors. Additionally, we control for industry-year effects, and cluster by time to allow for correlation in the cross-sectional error terms.

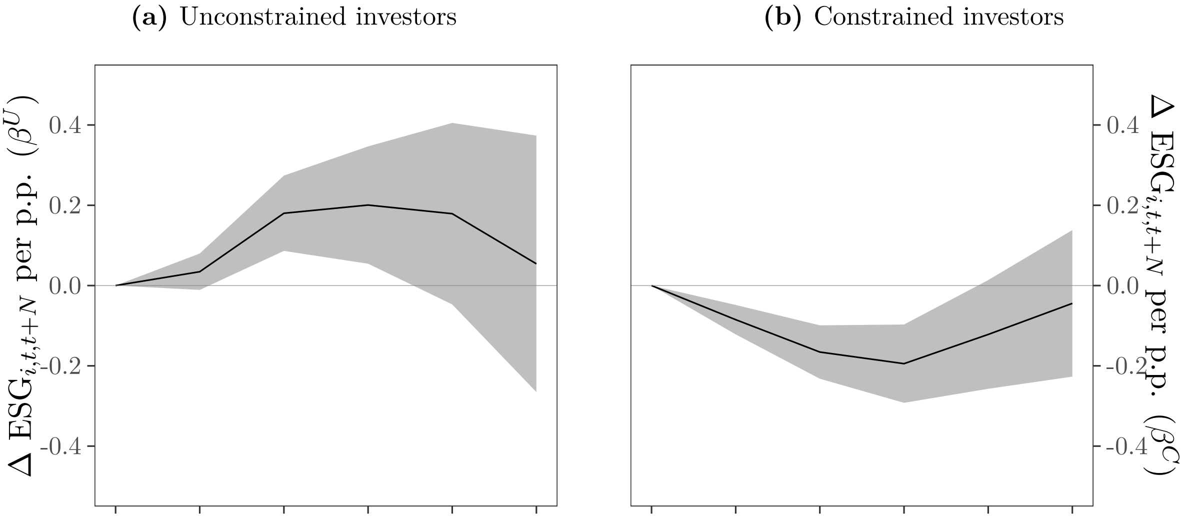


Figure 2a shows that an increase in ownership by socially unconstrained investors leads to future increases in the ESG score of the stock. We see that, if a stock is bought by an unconstrained investor, the stock experiences positive changes every year for three years in a row. The most significant yearly change is between year one and two, where it rises about 15 ESG points or half a standard deviation. This makes sense, as ESG scores can be updated from January to December, and therefore the second year will be the first time that the change reflects a whole year of ownership prior to the change. Had the stock remained in the hands of a socially constrained investor, however, see Figure 2b, its ESG score would decrease on average, though a little less than the increase for unconstrained.

This stylized fact indicates that socially unconstrained investors are better able to detect ESG firms with the potential of increases in their sustainability score. Unconstrained investors therefore seem to have superior skill to detect future ESG value, which may be explained by these investors spending a lot on fundamental analysis of companies, which they hope pays off through higher returns. Alternatively, it may be due to strong mandates preventing constrained investors from purchasing these promising stocks.

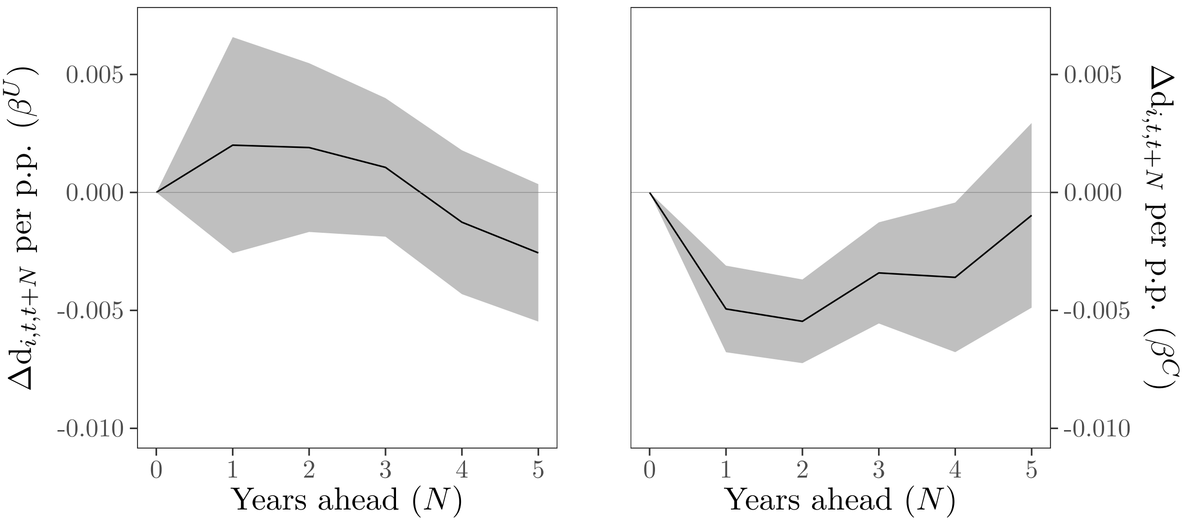
This finding can help explain why socially unconstrained investors earn superior returns when they invest in ESG firms. A firm with an undervalued ESG score could be of value for investors once the correct score materializes and the market prices in this new publicly available information. This would lead to price appreciation, which current holders would yield abnormal returns from. If this is true, then ESG score increases should lead to abnormal returns. We test this in the next section.

Before doing so, we conduct a robustness check to our findings in Figure 2. An alternative explanation to unconstrained investors being able to predict future ESG score increases could be that ESG score changes correlate with future cash flows. This would mean that unconstrained investors are really able to predict future cash flow changes rather than changing ESG scores. We test this by exchanging deltas in ESG scores by deltas in dividend yields and re-estimate Equation (10). Figure 3 shows our results.

We find that even though dividend yields tend to increase in the future when unconstrained ownership goes up, this effect is not significant. When socially constrained ownership increases, dividend yields decrease significantly. However, the magnitude in either case indicates this to be a small effect. We estimate this effect to be 0.2 bp and -0.5 bp per p.p. of ownership for socially unconstrained and constrained investors, respectively. We therefore conclude that changes in ESG scores depict a skill by unconstrained investors that is unlikely to be explained by changes in dividend yields.

Figure 3: Predicting dividend changes

Figure 3a shows socially unconstrained (U) ownership in firms and their correlation to future changes in dividends, whereas Figure 3b shows this effect for socially constrained (C) investors. Specifically, the β-estimate gives an indication for how much the dividend yield (in %) changes in N years ahead of time, when investor $I = \{U, C\}$ increases ownership by one percent today. Allowing for heteroskedasticity, the gray shade shows White standard errors. We control for firm fixed effects, and cluster by time to allow for correlation in the cross-sectional error terms.



(a) Unconstrained investors

(b) Constrained investors

Returns to ESG score changes

The second step is to see how changes in ESG scores affect returns. We test this by regressing returns onto ESG score changes, whilst controlling for risk (Equation H2 in Section 2).

As a standard panel-regression restricts each firm to have the same β, we also include a Fama-MacBeth specification, which allows the β estimates to vary at the firm level. Specifically, the difference of the Fama and MacBeth (1973) analysis is that instead of using the risk factors on a portfolio level, we first calculate each firm's exposure to the risk factors, their β, and thereafter use these β estimates in a panel-regression as risk controls at the firm level. In this second step, we run

$$r_i^e = \gamma_0 + \gamma_{mkt}\hat{\beta}_{i,mkt} + \gamma_{smb}\hat{\beta}_{i,smb} + \gamma_{hml}\hat{\beta}_{i,hml} + \gamma_{mom}\hat{\beta}_{i,mom} + \gamma_{\Delta ESG_t}\Delta ESG_{i,t} + \epsilon_i, \tag{11}$$

where $\hat{\beta}_{i,f}$ are firm-specific β estimates on the factor f. The change in ESG scores from the previous year to the current year t is denoted by $\Delta ESG_{i,t}$, where we have added a time subscript as we in the analysis also use $\Delta ESG_{i,t-1}$, which in turn is the change from two years ago to the previous year $t-1$. The variables of r_i^e and ϵ_i are the excess and unexplained return for firm i. Table 7 shows the results.

Table 7: Returns to ESG score increases in the cross-section

This table shows the results of a standard panel (column 1-2) as well as a Fama and MacBeth (1973) (column 3-4) cross-sectional regression approach including the changes in ESG scores on a yearly basis. The panel regression clusters standard errors on a firm level. The Fama and MacBeth (1973) approach first estimates $\hat{\beta}_j$ exposures for every firm and every risk factor j. In a second step, we regress excess returns against risk exposures for every time instance t, while including the exposure to changes in ESG scores. Specifically, the factor of ΔESG_t depicts the change in the ESG score of the firm that occurs in the current year relative to the last year. In a second approach we use ΔESG_{t-1} instead, documenting the change in the ESG score of the firm from two years ago to last year. We document t-test statistics below the coefficients.

	Dependent variable:			
	r^e			
	(1)	(2)	(3)	(4)
ΔESG_t	0.008*** t = 3.635		0.008*** t = 3.200	
ΔESG_{t-1}		0.002 t = 0.822		0.001 t = 0.620
mkt-rf	1.046*** t = 136.945	1.045*** t = 136.881		
hml	0.029** t = 2.439	0.029** t = 2.439		
smb	0.328*** t = 26.590	0.329*** t = 26.685		
mom	−0.144*** t = −20.856	−0.144*** t = −20.840		
$\hat{\beta}_{mkt}$			0.425 t = 1.074	0.425 t = 1.077
$\hat{\beta}_{smb}$			−0.241 t = −1.138	−0.241 t = −1.138
$\hat{\beta}_{hml}$			−0.135 t = −0.503	−0.140 t = −0.523
$\hat{\beta}_{mom}$			−0.066 t = −0.134	−0.069 t = −0.140
γ_0			0.736*** t = 4.638	0.758*** t = 4.924
Observations	107,310	107,310	107,308	107,308
R^2	0.235	0.235	0.390	0.390
Note:				*p<0.1; **p<0.05; ***p<0.01

We find that changes in ESG scores in the current year lead to positive excess returns, see Columns 1 and 3. If a firm, for example, has an ESG score of 30, but gets a higher score during the current year of 80, our results indicate that the excess return increases by 40 bp, or equivalently 10 bp for a standard deviation move in the ESG score. We do not observe any effect for lagged ESG score changes (Columns 2 and 4), suggesting that the returns are realised as the new score gets published.

One might be worried that returns could be confounded by dividend changes. Specifically, if dividend increases are associated with a positive return, and dividend increases are correlated with ESG changes, ESG changes could pick up the return effect from the increase to the cash flows. We control for this in Table 8.

Table 8: Robustness test of returns to ESG score increases controlling for cash flow changes

This table shows the results of a Fama and MacBeth (1973) cross-sectional regression approach including the changes in ESG scores on a yearly basis and the dividend return. The Fama and MacBeth (1973) approach first estimates $\hat{\beta}_{i,j}$ exposures for every firm i and every risk factor j. In a second step, we regress excess returns against risk exposures for every time instance t, while including the exposure to changes in ESG scores and dividends. Specifically, the factor of ΔESG depicts the change in the ESG score of the stock that occurs in the current year relative to the last year. d depicts the dividend return, and Δd is its yearly change. Column (1) documents results for the excess return r^e, and Columns (2-5) for $r^{e,exd}$ the excess return purely coming from price changes and not dividends. We document t-test statistics below the coefficients.

	Dependent variable:				
	r^e	$r^{e,exd}$			
	(1)	(2)	(3)	(4)	(5)
ΔESG	0.008^{***} t = 3.200	0.009^{***} t = 3.491		0.008^{***} t = 3.217	0.009^{***} t = 3.544
Δd			-0.551^{***} t = −4.148		-0.561^{***} t = −4.205
d				-0.887^{***} t = −11.722	
$\hat{\beta}_{mkt}$	0.425 t = 1.074	0.460 t = 1.164	0.440 t = 1.110	0.428 t = 1.083	0.439 t = 1.104
$\hat{\beta}_{smb}$	−0.241 t = −1.138	−0.195 t = −0.923	−0.167 t = −0.777	−0.230 t = −1.090	−0.166 t = −0.775
$\hat{\beta}_{hml}$	−0.135 t = −0.503	−0.187 t = −0.697	−0.218 t = −0.817	−0.144 t = −0.535	−0.212 t = −0.791
$\hat{\beta}_{mom}$	−0.066 t = −0.134	−0.062 t = −0.126	−0.095 t = −0.192	−0.058 t = −0.118	−0.087 t = −0.176
γ_0	0.736^{***} t = 4.638	0.538^{***} t = 3.381	0.565^{***} t = 3.624	0.712^{***} t = 4.578	0.545^{***} t = 3.400
Observations	107,308	107,308	107,308	107,308	106,983
R^2	0.390	0.389	0.391	0.392	0.391
Note:					$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

To be able to control for dividends we consider returns exclusively coming from price changes, so they do not include returns coming mechanically from dividend payments. Columns 1 and 2 show that the results for the total excess return and excess return excluding dividends are very similar; the ESG effect increases a little when excluding dividend returns. In Column 3 we see that changes in the dividend return from a year ago are associated with a negative return. This is similar when considering just the dividend return as in Column 4. Finally, in Column 5 we include both and see that the ESG effect remains constant. Table D.2 in Appendix D shows the same results but for total returns. These robustness results are very similar to our baseline results, except that the dividend effect is not significant. Our findings show that cash flow changes are not a confounding factor for returns arising from changes to ESG scores.

Together, the current and previous results confirm our second hypothesis, that is, unconstrained investors profit from sustainable investing by predicting ESG scores.

Constrained investors' purchases of high ESG stocks from unconstrained investors

As a third step, we provide further evidence on how unconstrained investors profit from sustainable investing. Our previous results show that unconstrained investors buy stocks, which later experience an increase in their ESG scores, earning them a return. Whilst we see for both types of investors that high ESG stocks rise in value when purchased, this return is not sustained for the constrained investors. This suggests that unconstrained investors benefit from finding underscored ESG firms by later selling them off, perhaps to the constrained investors, which may be bound by their mandate to only invest in stocks with some of the highest ESG scores. To test this formally, we check whether constrained investors indeed purchase high ESG firms from unconstrained investors. This also serves as a test of where the ESG demand arises from.

Specifically, we compare the change in constrained ownership of two types of stocks. We test if constrained investors purchase more high ESG stocks mainly held by unconstrained investors versus high ESG stocks mainly held by other investors. In other words, we compute

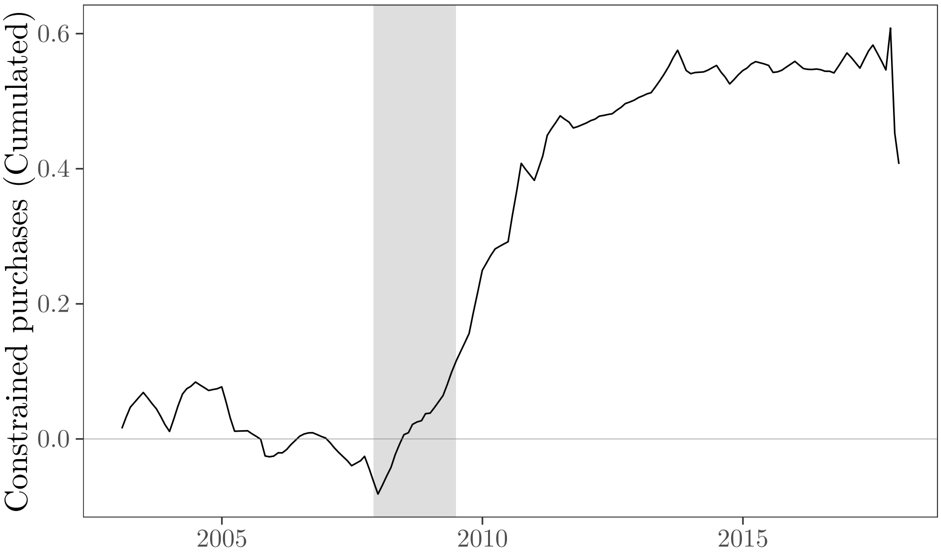
$$Purchase_t^C = \Delta Ownership_t^{C^{HESG,HU}} - \Delta Ownership_t^{C^{HESG,LU}},$$

where $\Delta Ownership_t^{C^{HESG,HU}}$ represents the quarterly change in the constrained ownership share in the high ESG and high unconstrained ownership portfolio. Similarly, we compute the quarterly change in constrained ownership in the high ESG but low unconstrained ownership portfolio through $\Delta Ownership_t^{C^{HESG,LU}}$. Hence, $Purchase_t^C$ exhibits how much more constrained owners purchase their high ESG stocks from unconstrained investors compared to other investors.

We plot the time series of results in Figure 4. The results show that constrained investors demand and purchase high ESG score stocks held by the unconstrained investors. They have been buying these stocks since the outbreak of the financial crisis and over time built up a significant positive cumulated ownership share.

Figure 4: Ownership changes between unconstrained and constrained investors

This figure shows the the difference in ownership shares in the high ESG and high versus low unconstrained ownership portfolio with respect to the ownership share of constrained investors (C). This means we first calculate the delta of constrained ownership levels in the high ESG and high unconstrained ownership portfolio over time. In a second step, we subtract the delta of the high ESG and low unconstrained ownership portfolio over time. Thereby, a positive difference indicator at time t suggests that constrained investors indeed buy high ESG and high return (see Table 2) stocks from unconstrained investors. This indicator is calculated on a quarterly basis.



These findings shed light on how unconstrained investors profit from sustainable investing (Equation H2 in Section 2). In a nutshell, unconstrained investors are able to predict ESG score changes (Figure 2); these ESG score changed lead to higher returns (Table 7), which they capitalize on (Table 2) by selling these stocks to constrained investors (Figure 4). As a result, unconstrained investors are able to exploit an ESG premium in the cross-section of firms.

4.3 Sentiment in sustainable investing

We go on to test our third hypothesis, stating that the ESG premium can be influenced by climate sentiment. As documented in Equation H3 in the theory section, unexpected increases in sustainability sentiment can lead to a positive ESG return even though the unconditional ESG premium is negative. This can help explain the positive returns earned by unconstrained investors. In the remaining section, we first consider sentiment in the form of our own climate salience measure.

Secondly, to ensure validity of our measure, we document how it compares to the Engle et al. (2020) climate change news measure, the Baker and Wurgler (2006) investor sentiment measure, and measures of optimism in the economy from valuation ratios.

To test for the effects of investor sentiment, we consider the returns of a long-short equity portfolio, which goes long in high ESG firms and short in low ESG firms. The analysis utilizes three main proxies for sentiment in addition to our own. Our own measure is explained in Section 3. The three external proxies are the Engle et al. (2020) climate change news sentiment, which is a dummy variable that is 1 when the negative climate news proxy based on the Wall Street Journal is above its unconditional average, and 0 otherwise. Second, the sentiment index by Baker and Wurgler (2006) serves as an indicator for investor behavior in the stock market. Finally, we use the price-dividend ratio as denoted by Robert Schiller.

When conducting our analysis, we compute

$$LS_t^I = r_t^{HESG,I} - r_t^{LESG,I} = \alpha + \gamma \ Sentiment_t + Controls_t + \epsilon_t, \tag{12}$$

where $r_t^{HESG,I}$ ($r_t^{LESG,I}$) depicts the high (low) ESG portfolio return of investor I at time t. The abnormal return is denoted by α. The investor sentiment at time t is denoted by $Sentiment_t$ with a loading of γ. Moreover, the controls always include the factors f_j together with their loadings β_j for all J factors, and sometimes a crisis indicator $\beta_{\mathbb{1}} \mathbb{1}_{NBER}$, which equals 1 in a crisis and 0 otherwise. Finally, ϵ_t is the unexplained return.

This is our empirical specification of Equation (H3), where α is the abnormal return due to the greenness of the firm, i.e. the greenness of the stock, multiplied by the return on the ESG portfolio $g\mu_g$. The notation of $\gamma Sentiment$ is the return from the preference shock, which also scales with the greenness of the firm gf_g. The variable f is the excess return on the factor (r_M^e in the theory specification). Hence, we expect γ to vary according to the greenness of the firm, and be especially pronounced in our factor as we capture the difference in greenness of the high and low ESG firms.

Climate salience

Sustainability sentiment could be driven by an increase in the salience of, for example, climate change risks. To test whether ESG stock returns illustrate evidence of sentiment, we test whether an adjusted time series of Google searches for ‘Climate change’, a proxy for sustainability salience, can explain the abnormal return of our ESG factor.

Table 9 shows the results. They confirm that climate salience indeed positively affects the returns to sustainable investing for the unconstrained investor (Columns 1 to 3), as well as for the general investor as seen by the ESG factor results (Columns 4 to 6).

Table 9: Sustainability sentiment from *Climate change* Google hits

In this table we test how climate sentiment explains abnormal returns for the sustainability strategy. The dependent variable for the first three columns is constructed a value-weighted long-short portfolio that goes long in top quartile of ESG firms within the top quartile of high socially unconstrained ownership and short in the low ESG but also high level of unconstrained ownership. The fourth to sixth column's dependent variable is constructed through a simple value-weighted long-short strategy that goes long in high and short in low ESG firms. We test for sentiment in these portfolios using a proxy for climate salience and economic sentiment. The measures we use is the surprise innovations in the Google Hits on the term 'Climate change', as described in Section 3, and the $NBER$ recession indicator, which equals 1 in a crisis and 0 otherwise. We control for risk-factors of the Carhart four-factor model, though results are similar for the CAPM and Fama-French three-factor models. Lastly, we control for autocorrelation and heteroscedasticity in the residuals using Newey and West (1987) standard errors with a lag length of 12 months.

	Dependent variable:					
	ESG Long-short return for:					
	Unconstrained (LS_t^U)			Factor (LS_t)		
	(1)	(2)	(3)	(4)	(5)	(6)
Climate salience	0.060***	0.060***		0.039**	0.038*	
	t = 3.120	t = 2.942		t = 1.992	t = 1.948	
α	0.396***			0.156		
	t = 2.692			t = 1.127		
NBER		1.108**	1.214***		0.440	0.303
		t = 2.468	t = 3.280		t = 1.092	t = 0.680
NBER$_{False}$		0.282	0.305*		0.111	0.096
		t = 1.523	t = 1.668		t = 0.729	t = 0.645
Climate:NBER			0.331***			−0.190*
			t = 2.907			t = −1.836
Climate:NBER$_{False}$			0.055**			0.041**
			t = 2.416			t = 2.103
mkt - rf	−0.036	−0.009	−0.029	−0.153***	−0.142**	−0.128**
	t = −0.625	t = −0.110	t = −0.379	t = −2.792	t = −2.572	t = −2.548
smb	−0.353***	−0.380***	−0.373***	−0.472***	−0.483***	−0.491***
	t = −3.288	t = −3.077	t = −3.209	t = −6.441	t = −6.542	t = −6.712
hml	0.115	0.131	0.165*	−0.048	0.042	0.069
	t = 1.438	t = 1.458	t = 1.916	t = −0.562	t = −0.463	t = −0.794
mom	0.139***	0.157***	0.147***	0.046**	0.053	0.058*
	t = 3.636	t = 3.116	t = 2.949	t = 1.738	t = 1.573	t = 1.970
Observations	155	155	155	156	156	156
R^2	0.236	0.268	0.281	0.453	0.458	0.467
Note:						*p<0.1; **p<0.05; ***p<0.01

In terms of magnitude, we see that a standard deviation shock to *Climate salience* is associated with a realized abnormal return from sustainable investing by unconstrained investors of 6 bp and

4 bp for the ESG factor in general. These estimates remain similar if we control for the crisis effects, however, investor groups performed quite differently during the crisis as the estimates rise for the unconstrained, but fall for the general factor.

As for robustness, we see that the results are not driven by the crisis, as the loading on sentiment is equally strong outside the crisis as seen by the Climate:NBER$_{False}$ interaction term. The results are consistent across the different asset pricing models: CAPM, Fama-French, and Carhart. The results are also robust to creating the factor on searches on 'Climate' and to using just the Google searches coming from the news part. Finally, the results are robust to using the changes in *Climate salience* instead of the AR(1) residual, as well as a non-seasonally adjusted time series.

These results support the idea that sustainability sentiment is a force that affects ESG stock valuations and can help explain the positive abnormal returns earned by unconstrained investors. Additionally, the results suggest that the value of predicting ESG scores might be higher in a period of high noise and uncertainty as the crisis.

Engle et al. (2020) climate change news

Sustainability sentiment could also be driven by an increase in the salience of, for example, climate change risks. To see if our ESG returns illustrate evidence of this type of sentiment, we test whether salience in the form of high negative news coverage of climate can explain returns of our ESG factor. Specifically, we regress our ESG factor on *chneg*, a dummy variable developed by Engle et al. (2020), that is 1 when there are more than average bad news on climate, and 0 otherwise.

Table 10 Column 1 documents our findings. Incorporating other risk factors, this type of salience indeed matters for the returns of our general ESG factor. In periods with more than average amounts of negative news, the factor documents 80 bp of abnormal returns, whereas in quiet periods it does not show any abnormal returns.

Baker and Wurgler (2006) investor measure

We also consider whether the classical measure of sentiment as developed by Baker and Wurgler (2006) can explain our ESG returns. We indeed find that there is some evidence for this conjecture as shown in Table 10 Column 2. We use their variable *perp*, which depicts their sentiment measure (a principal component of five proxies). We find that in periods with a higher than average amount of sentiment, there are no higher abnormal returns. Instead abnormal returns tend to be outside of their high sentiment periods (29 bp on average). Hence, it seems that sustainability sentiment is not correlated with general business sentiment. In fact, we see sustainability sentiment being especially strong in the recession.

Table 10: Other sustainability sentiment measures

We first sort returns according to lagged ESG scores in a total of 10 portfolios and value-weight them. We construct a long-short portfolio strategy that goes long in high ESG firms and short in low ESG firms (LS_t). We test for sentiment in this portfolio through three measures. In the first column and denoted by 'chneg' we test against the climate news series from Engle et al. (2020), which is either one in case of lots of news on climate change and 0 otherwise. The second column tests against the sentiment index by Baker and Wurgler (2006), which is one when sentiment is high and 0 otherwise. Finally, column 3 tests against log-changes in the price dividend ratio taken from Robert Schiller's data website. Additionally, we adjust for factor returns under the Carhart four-factor model. We control for autocorrelation and heteroscedasticity in the residuals using Newey and West (1987) standard errors with a lag length of 12 months.

	Dependent variable:		
		LS_t	
	(1)	(2)	(3)
chneg = 1	0.803^{***} t = 3.102		
chneg = 0	0.013 t = 0.084		
perp = 0		0.288^{*} t = 1.703	
perp = 1		−0.041 t = −0.202	
Δpd			-0.214^{**} t = −2.180
mkt - rf	-0.124^{**} t = −2.184	-0.155^{***} t = −2.883	−0.095 t = −1.532
smb	-0.573^{***} t = −6.765	-0.504^{***} t = −7.015	-0.496^{***} t = −6.860
hml	−0.003 t = −0.030	−0.063 t = −0.790	−0.081 t = −1.045
mom	0.073^{***} t = 2.674	0.047 t = 1.616	0.032 t = 1.217
α			0.068 t = 0.577
Observations	109	180	179
R^2	0.517	0.465	0.470
Note:			*p<0.1; **p<0.05; ***p<0.01

Business cycles

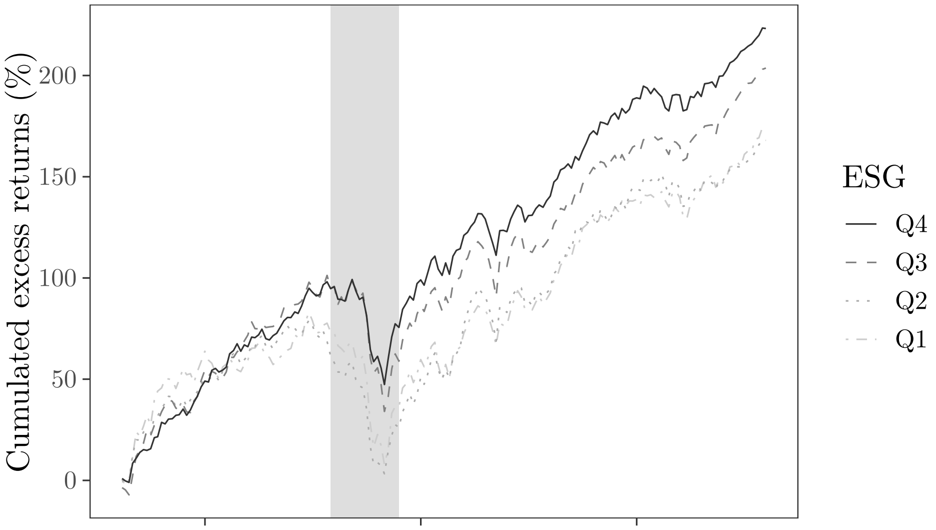
To further test whether investors' sustainability sentiment varies with general optimism in the economy, we test whether the ESG factor can be explained by developments in the dividend-price ratio in excess of traditional risk factors.

We find that a falling price dividend ratio is associated with increased returns on the ESG factor, see Table 10 Column 3. A 1% drop is associated with a decrease in the abnormal return of 21 bp. This finding additionally confirms that sustainability sentiment is negatively correlated with general business sentiment.

To illustrate the business cycle effects we plot cumulated excess returns of the four ESG portfolios within the ownership type of unconstrained investors in Figure 5. In this plot, Q4 refers to high, and Q1 for low ESG firms. It shows that especially high ESG firms with high socially unconstrained ownership seem to do better during the crisis.[20]

Figure 5: Cumulative excess returns for stocks with different ESG levels within high unconstrained ownership

This figure shows cumulative value-weighted returns for different ESG portfolios for stocks with high amounts of socially unconstrained ownership (top quartile). The portfolio Q1 (Q4) depicts the lowest ESG firms. The shaded area denotes the recession.



We again see that, although the top quartile has performed better throughout the sample, it also fell less in the crisis compared to the bottom two quartiles.

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[20] We additionally show the same plot for socially constrained investors in Figure IA.3. In the appendix, we furthermore show the long-short ESG portfolio for high degrees of socially unconstrained and constrained investors in Figure IA.4 and IA.5.

One argument for high ESG returns in the recession could be that as governments stimulate the economy, there is public pressure that monetary support is given to those firms which emphasize more sustainable business models as seen during the COVID-19 crisis.[21]

These findings provide additional empirical evidence that climate sentiment seems to correlate negatively with business cycles. In fact, sustainability sentiment may even rise during recessions.

5 Conclusion

We document an Environmental, Social and Governance (ESG) premium for stocks with a high degree of socially unconstrained ownership. A closer look reveals that this discrepancy arises from the unconstrained investors' ability to predict future increases in ESG scores, which earns additional return. This implies that constrained investors could potentially also see the same investment opportunities, but cannot exploit them due to their strict mandates. Instead, they chase high ESG and high return stocks but are unsuccessful in earning high returns once purchased. In the time series we see that growing climate sentiment boosts the returns earned by a sustainable investment strategy.

Interest in sustainable investing has been accelerating over the last decades, and recent government and institutional changes have only increased the pace of this growth. As more and more assets are invested under sustainable mandates, understanding this shift in preferences becomes increasingly important.

Our findings have real implications for investors as they show that sustainability is priced. From a corporate finance perspective, our findings have implications for its cost of capital. It decreases for sustainable firms. Hence, our paper shows that investors' preferences are already nudging the economy towards a more sustainable future. As this effect is only expected to increase, it will ultimately lead to more sustainable projects being financed.

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[21] See, for example, the IMF's emphasize and support for a "Green Recovery" to fight the aftermath of the pandemic: `https://www.imf.org/en/Topics/climate-change/green-recovery`.

Another argument is that investors care more about ethics in times of crises. For example, Sapienza and Zingales (2012) show that during the financial crisis we saw a rapid decline in the trust of the financial system, an observation validated by Jha et al. (2021), who confirm the findings for a measure of public sentiment towards finance.

Appendices

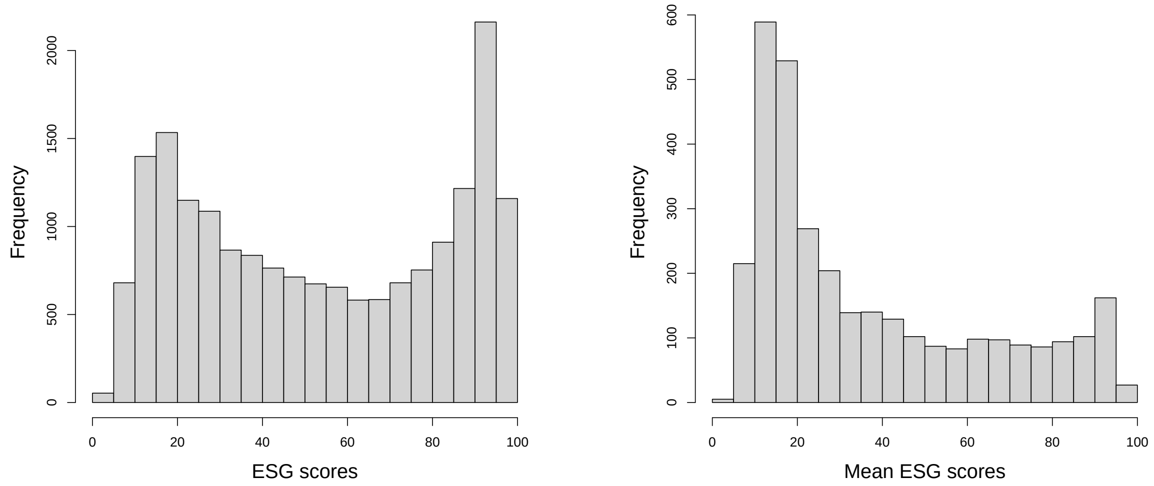
A ESG Scores

In this appendix, we describe our data on ESG scores in more detail. Figure A.1 shows the distribution of ESG scores across the firms and years in our sample. Additionally, Table A.1 documents the distribution across industries, means and volatility of ESG scores and mean returns of those industries. Finally, Table A.2 documents the names of companies that have high ESG scores in the beginning and end of the sample.

Figure A.1 plots ESG scores over all scores available and across companies' yearly averages. Interestingly, many scores place in the upper and lower score distribution, which suggests that a company would rather exhibit a low score than not having one at all despite the fact that a low score implies low sustainability.

Figure A.1: ESG distribution

Figure A.1a represents the distribution of all ESG scores across all firms. Figure A.1b averages the firms' yearly ESG scores, so that every firm exhibits only one average score.



(a) ESG scores **(b)** Mean ESG scores

We also distinguish between different types of industries according to SIC Codes. Table A.1 exhibits the results. The manufacturing industry represents the largest share of the sample with a total of 972 firms and a total of 65,476 observations. It also has the largest average score of above 58. Other well-represented industries are transportation, communications, electric gas and sanitary services, finance, insurance, and real estate as well as services. Hence, all findings are driven by these industries rather than others. ESG scores vary heavily within most industries with volatility of up to 30 points.

Table A.1: ESG industry composition

We exhibit the total number of observations, number of firms, average ESG scores, ESG score volatility and equally-weighted average returns according to different types of industries.

	#observations	#firms	% of all firms	$\overline{ESG}$	σ_{ESG}	$\bar{r}$
Agriculture, Forestry and Fishing	202	8	0.269	26.123	13.771	1.292
Mining	8,162	136	4.571	47.260	26.544	1.090
Construction	2,445	38	1.277	37.639	23.993	1.309
Manufacturing	65,476	972	32.672	58.595	30.005	1.395
Transportation, Communications, Electric Gas and Sanitary service	20,296	288	9.681	53.195	29.804	1.069
Wholesale Trade	5,035	115	3.866	46.647	27.095	1.204
Retail Trade	12,210	180	6.050	53.691	28.545	1.308
Finance, Insurance and Real Estate	28,161	482	16.202	40.477	26.485	1.176
Services	23,724	453	15.227	40.670	26.473	1.423
PublicAdministration	24	1	0.034	14.745	0.312	0.941
Nonclassifiable	7,646	302	10.151	18.252	12.385	1.752

Out of 63 firms that were part of the highest decile ESG scores in 2002, a significant number of 33 were also part of this portfolio in the end of the sample, suggesting that ESG scores are sticky in the top decile, see Table A.2. Interestingly, also firms that one would think are not part of that group, as for example British American Tobacco PLC or Occidental Petroleum Corporation, are members of the high profile ESG group. This suggests that not the objective of the firm matters but instead how well the criteria to obtain a high score are fulfilled.

Table A.2: High profile ESG companies

The table exhibits companies of the highest decile ESG portfolio that were part of this prtfolio in both 2002 and 2016 (beginning and end of the sample). In total, we see 33 companies to be part of this group. The respective CUSIP codes can be used to access the companies' information through CRSP.

#	Name	CUSIP
1	A B B LTD	00037520
2	ABBOTT LABORATORIES	00282410
3	BANCO BILBAO VIZCAYA ARGENTARIA	05946K10
4	BANCO SANTANDER CENTRAL HISP SA	05964H10
5	BAXTER INTERNATIONAL INC	07181310
6	B H P LTD	08860610
7	BOEING CO	09702310
8	BRISTOL MYERS SQUIBB CO	11012210
9	BRITISH AMERICAN TOBACCO PLC	11044810
10	CHEVRON CORP	16676410
11	CISCO SYSTEMS INC	17275R10
12	DOW CHEMICAL CO	26054310
13	DU PONT E I DE NEMOURS & CO	26353410
14	DUKE ENERGY CORP	26441C20
15	EASTMAN CHEMICAL CO	27743210
16	ENBRIDGE INC	29250N10
17	GLAXOSMITHKLINE PLC	37733W10
18	HEWLETT PACKARD CO	40434L10
19	IMPERIAL OIL LTD	45303840
20	I N G GROEP N V	45683710
21	INTEL CORP	45814010
22	INTERNATIONAL BUSINESS MACHS COR	45920010
23	JOHNSON & JOHNSON	47816010
24	KONINKLIJKE PHILIPS ELEC N V	50047230
25	MERCK & CO INC	58933Y10
26	MOTOROLA INC	62007630
27	NOKIA CORP	65490220
28	OCCIDENTAL PETROLEUM CORP	67459910
29	PROCTER & GAMBLE CO	74271810
30	STMICROELECTRONICS NV	86101210
31	TEXAS INSTRUMENTS INC	88250810
32	MINNESOTA MINING & MFG CO	88579Y10
33	UNITED PARCEL SERVICE INC	91131210

B Sorting

Single-sorted portfolios. We start out by selecting only those firm-month observatiosn for which we have ESG information available for the previous year. Within these firms, we distinguish between different degrees of ESG scores. In total, we subdivide our sample into ten portfolios, ranging from the highest to the lowest decile ESG firms. Specifically, we sort returns according to the previous year's ESG scores. For example, ESG scores in 2002 determine our portfolios in 2003 and so forth.

We construct value-weighted decile portfolios for the entire data period, where P10 (P1) depicts the highest (lowest) ESG portfolio, where we use the market-value of a firm from the previous month as a proxy for value. We choose to value-weight, because portfolio returns would otherwise largely be driven by small firms.[22] However, one should note that the value composition between decile portfolios is not evenly distributed. Our data shows that high scores are primarily obtained by rather large firms, and vice versa. Finally, we use the self-developed portfolios to construct a long-short portfolio (LS), which goes long in the highest ESG decile portfolio and shorts the lowest ESG decile portfolio.

Double-sorted portfolios. We utilize ownership information to double-sort returns on two variables; that is, information on how high ownership by socially constrained and unconstrained investors is in a given firm. Specifically, we first sort firms for a given month based on the previous year's ESG scores into four portfolios. Thereafter, we conditionally sort on the level of ownership in the previous quarter, so that we end up with a total of 16 portfolios. These portfolios are re-balanced every month and rearranged every quarter as new holding data becomes available. Additionally, we incorporate the new ESG data in the rebalancing at year-end. As previously, we value-weight returns within the sorted portfolios. Additionally, we construct long-short portfolios according to ESG and ownership information.

Risk-adjusting returns. To risk-adjust returns, we use the CAPM, Fama-French three-factor or Carhart model (Carhart, 1997, Fama and French, 1992, Sharpe, 1964). This means we explicitly estimate

$$r_{it} - r_t^f = \alpha_i + \sum_{j=1}^{J} \beta_{ij} f_{jt} + \epsilon_{it}, \tag{B.1}$$

where r_{it} depicts portfolio i's return at time t. Moreover, r_t^f, α_i, and J denote the risk-free rate, the abnormal return, and the number of factors. Finally, β_{ij}, f_{jt} and ϵ_{it} are the factor loadings, factor returns, and the error term, where f corresponds to $\mu_M = r_M^e$ in our theory section under the CAPM model, and in general the factors of the specified risk-model.

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[22] Nevertheless, we conduct all analyses on an equally-weighted portfolio level as well for robustness checks.

C Sustainable Investing Facts

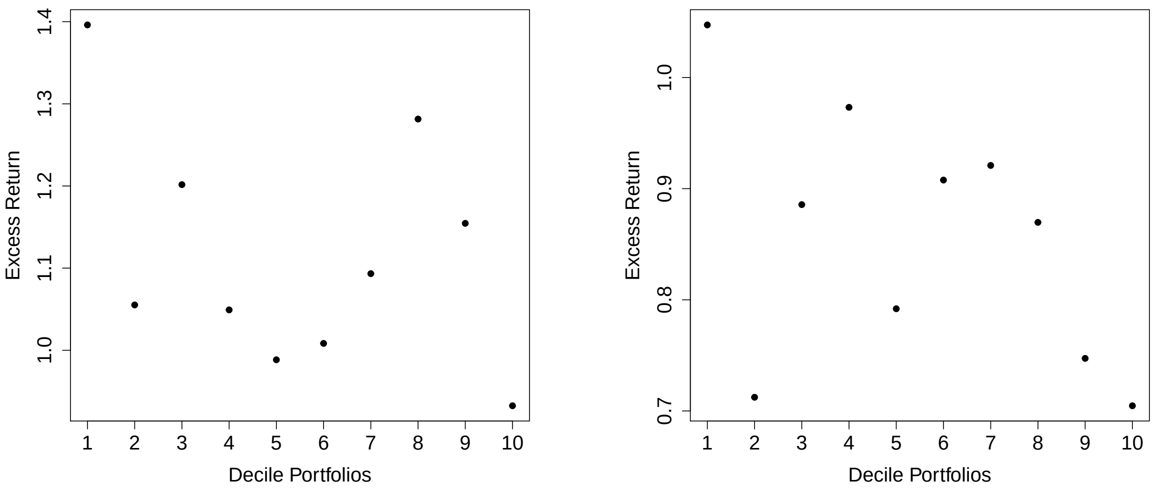
C.1 ESG portfolios and factor returns

This appendix documents summary statistics for our ESG-sorted returns. First, Figure C.1 shows the average return for each portfolio. Under both the equally-weighted and value-weighted approach, we see that returns are higher under the equally-weighted case. Neither provides evidence of a clear relationship between ESG scores and total returns.

Figure C.2 shows the returns of the ESG factor over time. We can see that it earned negative returns on average, but that it is fully explained through risk, see Table C.1. Additionally, we note the interesting fact that as the sentiment measure has a persistent effect, that is, a significant AR(1) coefficient, as observed in Figure 1 in Section 3, this helps explain why cumulative returns on the ESG factor follow a boom-bust pattern.

Figure C.1: Raw returns

The plots C.1a and C.1b exhibit decile portfolios' excess returns according to an equal- and value-weighted approach. The high (low) ESG decile portfolio *10* (*1*) depicts the firms with the highest (lowest) ESG scores. Portfolios are rearranged every year according to the previous year's ESG score.



(a) Equally-weighted

(b) Value-weighted

Figure C.2: Cumulative excess returns of ESG factor

We plot the value-weighted cumulated excess returns of a long-short portfolio that buys high ESG firms (top 10%) and shorts low ESG firms (bottom 10%). The portfolios are rearranged according to the previous year's ESG scores. The shaded area denotes the recession dates according to NBER.

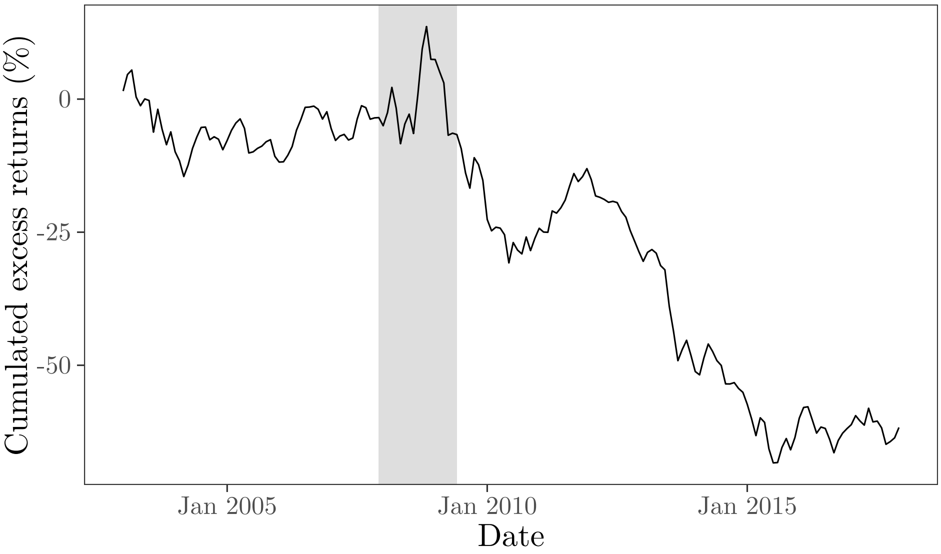


Table C.1: Value-weighted ESG factor

This table is an extension from *Panel B* in Table 3, in which we construct value-weighted decile portfolios based on previous year ESG scores and adjust them in the beginning of each calender year. We then construct a long-short strategy (LS_t), which goes long in high ESG firms and shorts low ESG firms. We risk-adjusted returns through the application of the CAPM, Fama-French 3-factor, Carhart 4-factor, and Fama-French 5-factor models. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months.

	Dependent variable:			
	LS_t			
	(1)	(2)	(3)	(4)
α	−0.148 t = −0.750	−0.133 t = −0.654	−0.166 t = −0.807	−0.331 t = −1.556
mkt-rf	-0.239^{**} t = −2.581	−0.148 t = −1.353	−0.103 t = −0.995	−0.048 t = −0.464
smb		-0.442^{***} t = −6.732	-0.455^{***} t = −7.479	-0.372^{***} t = −4.560
hml		0.118 t = 1.192	0.200^{**} t = 2.001	0.0001 t = 0.002
mom			0.142^{**} t = 2.255	
rmw				0.474^{***} t = 3.597
cma				0.422^{***} t = 3.408
Observations	180	180	180	180
R^2	0.121	0.241	0.284	0.331
Note:	*p<0.1; **p<0.05; ***p<0.01			

C.2 ESG and unconstrained investors

In this subsection, we show additional results on the returns of unconstrained investors when they invest sustainably.

Table C.2: Double sort of ESG and ownership of socially unconstrained investors

We first sort returns according to lagged ESG scores in a total of four portfolios. In a next step, we conditionally sort returns according to their previous quarter's socially unconstrained institutional ownership share and assign them into another four portfolios, ending up with a total of 16 portfolios. LS is the abnormal return from a long-short strategy which goes long in high ESG firms and short in low ESG firms. We value-weight these 16 portfolios with the previous month's market values. Finally, we run regressions according to the CAPM and Carhart models and display alphas as well as relevant t-test statistics. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months. Bold numbers represent statistical significance at a level of 5% or below.

	ESG low	Q2	Q3	ESG high	LS
Panel A: CAPM					
Unconstrained ownership low	0.000	-0.086	-0.052	0.161	0.161
t-stat	-0.002	-0.75	-0.318	1.335	0.704
Q2	0.059	0.049	-0.159	0.012	-0.047
t-stat	0.480	0.39	-1.089	0.138	-0.258
Q3	0.020	0.000	0.011	0.004	-0.016
t-stat	0.126	0.001	0.086	0.032	-0.090
Unconstrained ownership high	0.079	0.020	0.186	**0.400**	**0.321**
t-stat	0.645	0.141	1.187	3.889	2.211
Panel B: Carhart					
Unconstrained ownership low	0.021	-0.064	-0.030	0.169	0.148
t-stat	0.123	-0.540	-0.177	1.278	0.565
Q2	0.046	0.065	-0.151	0.019	-0.027
t-stat	0.347	0.506	-1.067	0.210	-0.130
Q3	-0.033	-0.017	0.024	0.007	0.041
t-stat	-0.228	-0.121	0.191	0.057	0.217
Unconstrained ownership high	0.088	0.005	0.173	**0.392**	**0.304**
t-stat	0.773	0.041	1.202	3.784	2.027

D Robustness Results

In this section, we show robustness results.

Table D.1: Robustness test for risk-adjusted returns under unconstrained ownership and sustainability using different models

We sort returns according to lagged scores in a total of four portfolios based on ASSET4 (A4), Sustainalytics (S), Sustainalytics Environment (S:E) and Carbon per Revenue (CO2) scores. Data goes from 2002 until 2016 under ASSET4 and 2011 until 2016 otherwise. In a next step, we conditionally sort returns according to their previous quarter's socially unconstrained institutional ownership share and assign them into another four portfolios, ending up with a total of 16 value-weighted portfolios. In another step, we construct value-weighted and risk-adjusted returns according to the CAPM, Fama-French three-factor, and Carhart four-factor model for a portfolio that goes long in high score (low score for CO2 metric) firms with high socially unconstrained ownership. We adjust standard errors according to Newey and West (1987) with a lag of 12 months and report relevant coefficients and t-values.

	Dependent variable:											
	A4			S			S:E			CO2		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
α	0.400^{***}	0.392^{***}	0.392^{***}	0.352^{***}	0.399^{***}	0.384^{***}	0.337^{**}	0.392^{***}	0.372^{***}	0.513^{**}	0.556^{***}	0.585^{***}
	t = 3.889	t = 3.705	t = 3.784	t = 3.124	t = 4.154	t = 4.579	t = 2.266	t = 3.116	t = 3.051	t = 2.556	t = 3.335	t = 4.080
mkt-rf	0.961^{***}	0.987^{***}	0.987^{***}	0.977^{***}	0.955^{***}	0.963^{***}	1.000^{***}	0.978^{***}	0.988^{***}	1.068^{***}	1.061^{***}	1.046^{***}
	t = 48.180	t = 35.163	t = 39.925	t = 17.886	t = 14.574	t = 13.709	t = 20.391	t = 15.559	t = 13.789	t = 18.443	t = 17.203	t = 16.699
smb		−0.042	−0.042		0.134^{**}	0.134^{**}		0.149^{**}	0.150^{**}		0.090	0.088
		t = −0.594	t = −0.594		t = 2.077	t = 2.113		t = 2.233	t = 2.296		t = 0.796	t = 0.763
hml		-0.090^{*}	-0.091^{*}		-0.191^{***}	-0.177^{***}		-0.289^{***}	-0.271^{***}		-0.401^{***}	-0.427^{***}
		t = −1.704	t = −1.690		t = −3.147	t = −2.775		t = −4.363	t = −4.350		t = −2.602	t = −3.057
mom			−0.001			0.023			0.029			−0.042
			t = −0.039			t = 0.357			t = 0.456			t = −0.647
Observations	180	180	180	72	72	72	72	72	72	72	72	72
R^2	0.874	0.877	0.877	0.795	0.815	0.816	0.759	0.796	0.797	0.679	0.731	0.732

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table D.2: Robustness of returns from ESG score increases controlling for cash flow changes using total returns

This table shows the robustness results of a Fama and MacBeth (1973) cross-sectional regression approach including the changes in ESG scores on a yearly basis and the dividend return for total excess returns r^e. The Fama and MacBeth (1973) approach first estimates $\hat{\beta}_{i,j}$ exposures for every firm i and every risk factor j. In a second step, we regress excess returns against risk exposures for every time instance t, while including the exposure to changes in ESG scores and dividends. Specifically, the factor of ΔESG depicts the change in the ESG score of the stock that occurs in the current year relative to the last year. d depicts the dividend return, and Δd is its yearly change. We document t-test statistics below the coefficients.

	Dependent variable:			
	r^e			
	(1)	(2)	(3)	(4)
ΔESG	0.008^{***}		0.008^{***}	0.008^{***}
	t = 3.200		t = 3.217	t = 3.300
Δd		−0.046		−0.057
		t = −0.352		t = −0.430
d			0.113	
			t = 1.499	
$\hat{\beta}_{mkt}$	0.425	0.408	0.428	0.407
	t = 1.074	t = 1.028	t = 1.083	t = 1.023
$\hat{\beta}_{smb}$	−0.241	−0.220	−0.230	−0.219
	t = −1.138	t = −1.026	t = −1.090	t = −1.023
$\hat{\beta}_{hml}$	−0.135	−0.160	−0.144	−0.153
	t = −0.503	t = −0.596	t = −0.535	t = −0.572
$\hat{\beta}_{mom}$	−0.066	−0.090	−0.058	−0.082
	t = −0.134	t = −0.183	t = −0.118	t = −0.166
γ_0	0.736^{***}	0.750^{***}	0.712^{***}	0.732^{***}
	t = 4.638	t = 4.826	t = 4.578	t = 4.581
Observations	107,308	106,983	107,308	106,983
R^2	0.390	0.390	0.391	0.391
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$	

Internet Appendix for:
Skills and Sentiment in Sustainable Investing

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Abstract

This Internet Appendix shows robustness checks and additional results outside of the main analysis of the paper. Specifically, we show more results on ESG ownership and preferences, robustness tests for our ESG premium under both unconstrained and constrained investor ownership as well as additional findings with respect to sentiment considerations in the dynamics of returns. Finally, we show additional portfolio sorts for other variables of interest.

IA.1 ESG Ownership and Preferences

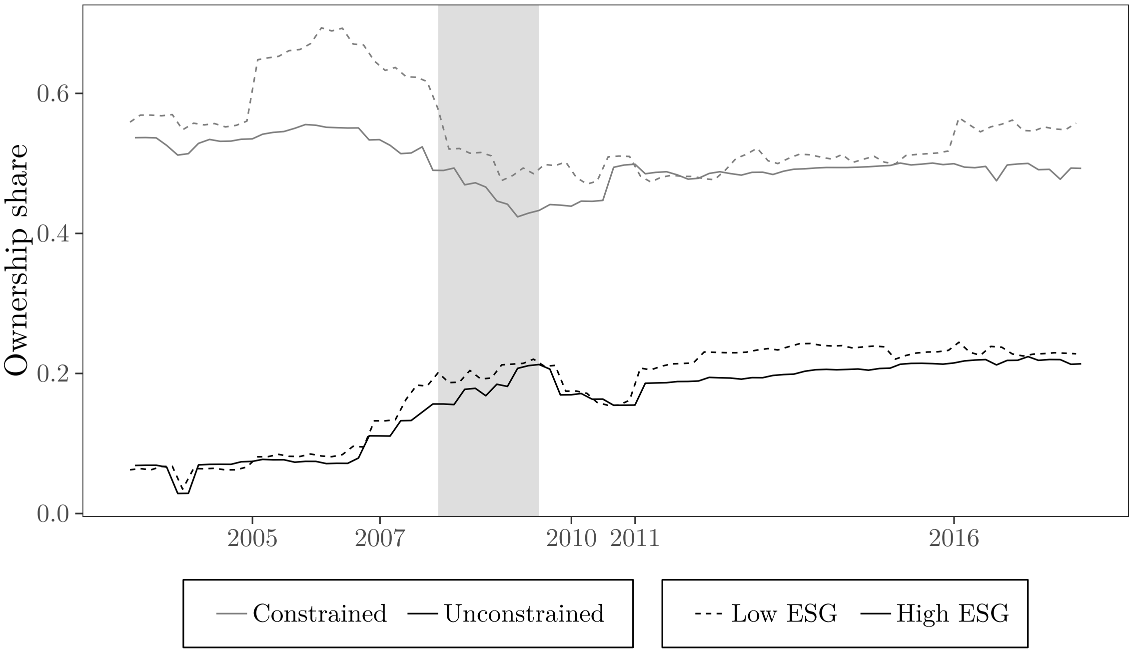
Ownership

In this subsection, we review our findings on ownership of ESG stocks. Specifically, we consider our two ownership groups.

Figure IA.1 plots the relative ownership of socially constrained and unconstrained owners in firms with ESG scores. Specifically, we subdivide into four portfolios, which we rearrange every year in the sample according to the previous year's score. We value-weight the time series and plot ownership over time. The 1st quartile are low ESG firms, whereas the 4th quartile represents high ESG firms.

Figure IA.1: ESG ownership

We plot the ownership structures of firms with ESG scores. We subdivide the sample of ESG firms in four different portfolios and rearrange them every year according the previous year's ESG score. The 1st quartile (4th quartile) includes firms with the lowest (highest) ESG scores. Holdings are value-weighted. At the top in grey, we exhibit the ownership share (relative to shares outstanding) of socially constrained owners of all ESG firms. Socially constrained investors are either banks (Type 1), insurance companies (Type 2) or other institutions (Type 5). Below in black the ownership concentration of socially unconstrained investors in ESG firms is shown. Socially unconstrained investors are either mutual funds (Type 3) or independent investment advisors (Type 5). The shaded area denotes recession.



The level of ownership by socially constrained investors seems to be more volatile in low ESG firms, see Figure IA.1. This might relate to findings by Starks et al. (2017), suggesting that long-term investors are less patient with low ESG firms than with high ESG firms. The total level of socially constrained and unconstrained owners is lower in high ESG firms. This might be due to retail investors (who make out the remainder of the ownership share) having a larger ESG tilt, making them own more relative to institutional investors.

With respect to socially unconstrained investors there is not much difference between relative shares of ownership among different levels of ESG. However, Figure IA.1 shows a large increase in total ownership of socially unconstrained ownership between 2006 and 2009. We further notice that the difference in ownership shares between the two ownership groups narrows in the crisis.

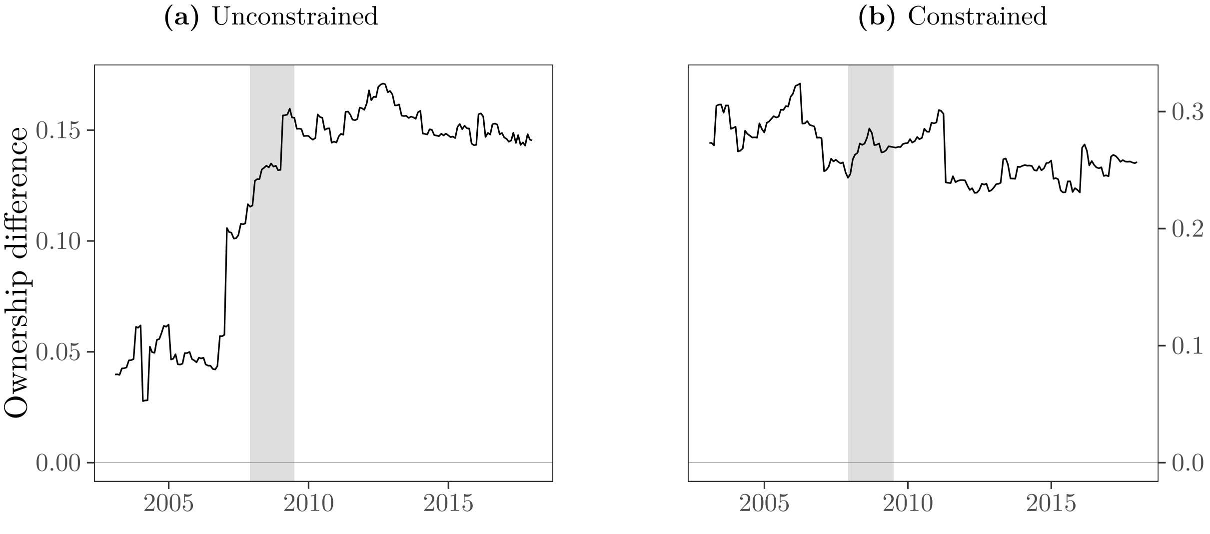
It is further interesting to note that portfolio tilts (difference in ownership of high and low ESG stocks) become smaller in the crisis as risk aversion increases. To connect this with theory, it may be because retail investors, who may have the highest ESG preference, increased their high ESG ownership in the good years before the crisis, and then reduced their tilt in the crisis, which would mean that constrained and unconstrained investors had to pick up the difference.

Preferences

To get an understanding of preferences, we plot portfolios with high and low degrees of socially constrained and unconstrained ownership within high and low ESG firms in Figure IA.2. This gives us an idea about the heterogeneity of ESG preferences within the two investor types. The idea is that if everyone valued ESG equally, you would not have some tilting towards higher ESG firms, leading to everyone owning the same ownership share of high ESG stocks, and a small difference between the high ESG stocks with the highest ownership share and lowest ownership share as plotted in Figure IA.2. On the other hand if there is a large heterogeneity of prefences we would expect to see a large difference between the investors' ownership of high ESG stocks. It turns out that the latter is what we see in the data. Specifically, what we see is that there is a large preference heterogeneity within constrained investors across the whole period, and that preference heterogeneity in the beginning was low for the unconstrained, but that it grew from around 2007, as well as through the financial crisis, to finally be several orders of magnitude larger by 2011. We acknowledge that this is not a perfect proxy, but we think it serves as a useful measure of ESG preference heterogeneity.

Figure IA.2: ESG preferences

We plot the difference in institutional ownership among low and high ESG firms with either low or high ownership concentration. We use the quartile with most ownership and subtract the quartile with the least. The results are value weighted. In Figure IA.2a, we plot results for socially unconstrained investors. Socially unconstrained investors are either mutual funds (Type 3) or independent investment advisors (Type 5). Figure IA.2b shows ownership concentration of socially constrained investors in ESG firms. Socially constrained investors are either banks (Type 1), insurance companies (Type 2) or other institutions (Type 5). The shaded area denotes the recession.


(a) Unconstrained

(b) Constrained

The results show that differences between low and high ownerships shares range from about 15% to 25% within the socially unconstrained and constrained owners in the end of the sample, respectively. This is important from a theoretical point of view, as it suggests that investors indeed value ESG, and some do so more than others.

We further consider correlations between ESG scores and ownership, now looking how different investor types allocate their capital across firms with different ESG scores. We calculate the absolute value of holdings ($V_{i,t}^I$) in firm i at time t according to

$$V_{i,t}^I = S_{i,t} \times O_{i,t}^I \times P_{i,t}, \tag{IA.1}$$

where $I = \{U, C\}$ is the ownership type unconstrained or constrained. $S_{i,t}$, $O_{i,t}^I$ and $P_{i,t}$ are the total number of shares, the relative degree of ownership of investor I and the price of firm i at time t.

We use the data to test correlations between holding decisions and ESG scores according to the linear panel regressions of

$$V_{i,t}^I = ESG_{i,t-1} + F_i + \epsilon_{i,t} \tag{IA.2}$$

where $ESG_{i,t-1}$ is the ESG score of firm i at time $t-1$ (previous year's ESG scores), F_i is the firm fixed effects, and $\epsilon_{i,t}$ is the error term. Table IA.1 shows the results.

Table IA.1: Revealed preferences: ESG score portfolio tilts

We run regression (IA.2) for socially constrained (C) and unconstrained (U) owners. We control for firm fixed effects. The variable V^I, $I = \{U, C\}$, depicts the absolute invested capital. ESG scores are from the previous firm year of a given firm, i.e. the published score. The observations are updated on a yearly basis as ESG scores change once a year. Standard errors are clustered by firm and t-test statistics are shown in parentheses below.

	Dependent Variable:	
	V^C	V^U
ESG Score	59,839***	41,160***
	(7,541)	(3,959)
Firm Fixed Effects	Y	Y
Clustered Errors	Y	Y
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table IA.1 shows that both socially constrained and unconstrained investors increase their asset allocation with an increase in ESG scores. An increase in the ESG score by one point by one firm leads to an increase in capital allocated of roughly between 41 to 60 Thousand USD per investor type. We notice that constrained investors have a stronger preference for ESG, as they are about 50% more sensitive to firms' ESG scores. A revealed preference argument would therefore be that investors generally care about ESG, however, constrained investors seem to assert a higher preference to ESG than unconstrained investors.

IA.2 Additional Robustness Checks, Figures and Tables

This section provides additional figures and tables to give additional insight into our empirical setting. This includes ESG portfolio performance among socially constrained investors, see Figure IA.3, as well as an overview of cumulated excess returns for the ESG strategy among socially unconstrained owners in Figure IA.4 and constrained owners in Figure IA.5. Furthermore, we exhibit results of the double-sort methodology of ESG scores and socially constrained investors, see Table IA.2. Also, we show additional results for our sentiment analysis, see Table IA.3 and IA.4. Finally, we document additional results on risk-adjusted returns and double sorts according to market value and ownership concentration in Table IA.5 and IA.6, respectively.

Additional figures

Figure IA.3: Cumulative excess returns for stocks with different ESG levels and high socially constrained ownership

This figure shows cumulative returns for different ESG portfolios for stocks with high amounts of socially constrained ownership (top quartile). The portfolio Q1 (Q4) depicts the lowest (highest) ESG firms. The shaded area denotes the recession.

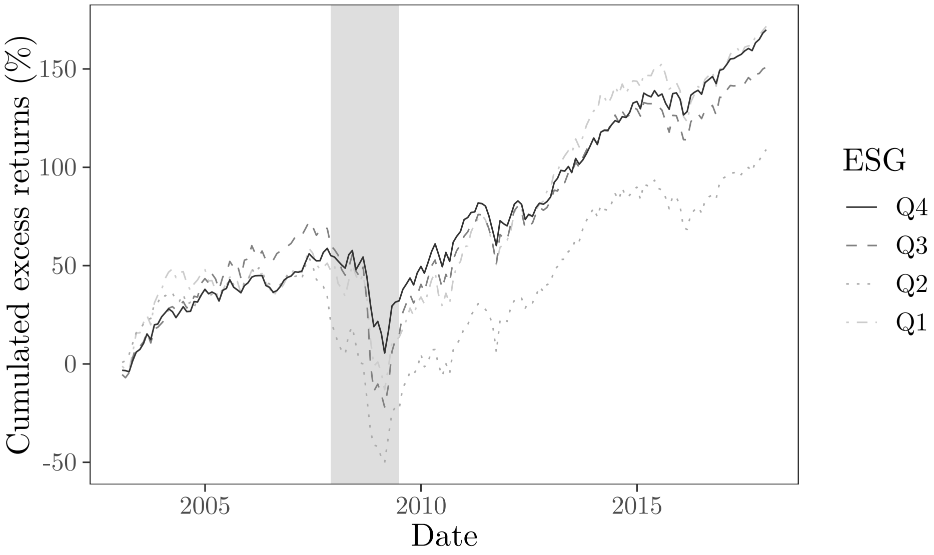


Figure IA.4: Cumulative excess returns of long-short portfolio for stocks with the largest fraction of socially unconstrained owners

This figure shows cumulative returns for a value-weighted long-short strategy, which goes long in the highest ESG and high socially unconstrained ownership quartile portfolio and short in the low ESG and high socially unconstrained ownership quartile portfolio. The shaded area denotes the recession.

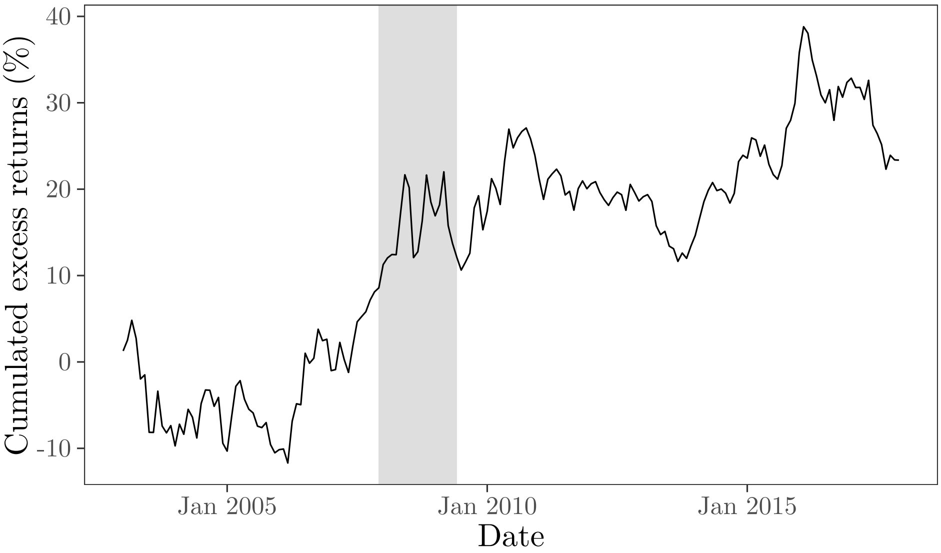
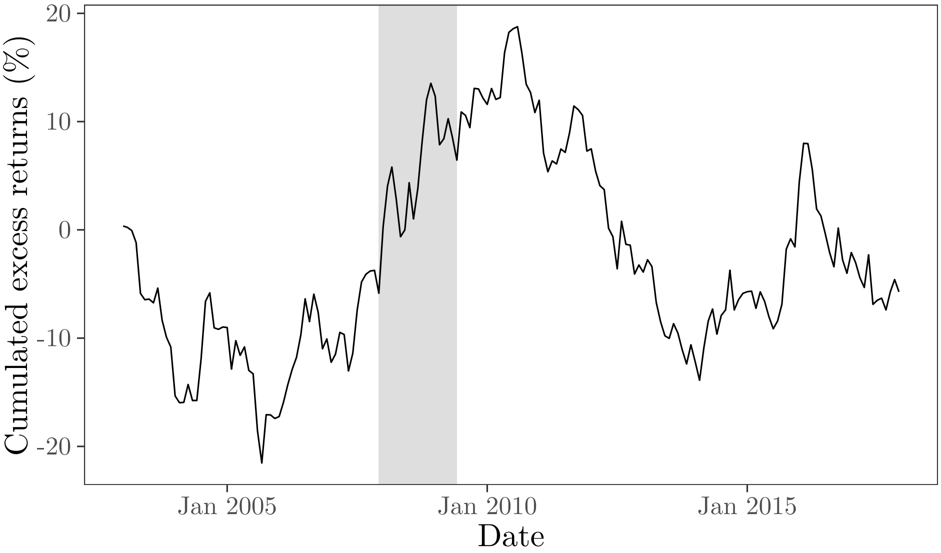


Figure IA.5: Cumulative excess returns of long-short portfolio for stocks with the largest fraction of socially constrained owners

This figure shows cumulative returns for a value-weighted long-short strategy, which goes long in the highest ESG and high socially constrained ownership quartile portfolio and short in the low ESG and high socially constrained ownership quartile portfolio. The shaded area denotes the recession.



Additional tables

Table IA.2: Long-short regressions and socially constrained ownership

We first sort returns according to lagged ESG scores in a total of four portfolios. In a next step, we conditionally sort returns according to their current quarter's socially constrained institutional ownership share and assign them into another four portfolios, ending up with a total of 16 portfolios, which we value-weight. We construct a long-short portfolio (LS_t^D) that goes long in high ESG firms and short in low ESG firms with either a high (H) or a low (L) level of socially constrained ownership as denoted by $D = \{H, L\}$. We test our long-short portfolio against the CAPM, Fama-French three-factor as well as the Carhart four-factor model. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months.

	Dependent variable:					
	ESG Long-short return for High or Low degree of constrained ownership, LS_t^D, $D = \{H, L\}$:					
	LS_t^H			LS_t^L		
	(1)	(2)	(3)	(4)	(5)	(6)
α	0.136	0.158	0.179	0.292	0.299	0.273
	t = 0.838	t = 0.966	t = 1.089	t = 1.241	t = 1.184	t = 1.027
mkt - rf	-0.179^{***}	-0.137^{***}	-0.166^{***}	-0.214^{**}	-0.125	-0.090
	t = −3.579	t = −2.655	t = −3.162	t = −2.351	t = −1.256	t = −0.872
smb		-0.307^{***}	-0.299^{***}		-0.378^{***}	-0.389^{***}
		t = −3.679	t = −3.518		t = −3.832	t = −3.910
hml		0.207^{***}	0.156^{**}		0.037	0.100
		t = 2.762	t = 2.271		t = 0.345	t = 0.945
mom			-0.090^{**}			0.110^{*}
			t = −2.081			t = 1.693
Observations	180	180	180	180	180	180
R^2	0.084	0.176	0.198	0.081	0.155	0.176

Note: *p<0.1; **p<0.05; ***p<0.01

Table IA.3: Sustainability sentiment in different economic times

We first sort returns according to lagged ESG scores in a total of four portfolios. In the next step, we conditionally sort returns according to their previous quarter's socially unconstrained institutional ownership share (U) and assign them into another four portfolios, ending up with a total of 16 value-weighted portfolios. We construct long-short portfolios that go long in high ESG firms and short in low ESG firms, all with high socially unconstrained ownership (LS_t^U). We test return performance of this portfolio in different times as denoted by whether the price-dividend ratio is above or below the unconditional mean. When the price dividend ratio is higher than the unconditional mean, good PD equals 1, and 0 otherwise. The variable bad PD equals 1 if the price dividend ratio is below the unconditional mean, and 0 otherwise. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months.

	Dependent variable:		
	LS_t^U		
	(1)	(2)	(3)
bad PD	0.387	0.395	0.430
	t = 1.355	t = 1.489	t = 1.643
good PD	0.252	0.264	0.173
	t = 0.869	t = 0.983	t = 0.645
mkt - rf	-0.168^{***}	-0.053	-0.015
	t = -3.279	t = -1.003	t = -0.273
smb		-0.491^{***}	-0.502^{***}
		t = -5.554	t = -5.759
hml		0.055	0.123
		t = 0.682	t = 1.465
mom			0.118^{**}
			t = 2.506
Observations	180	180	180
R^2	0.063	0.204	0.232
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Table IA.4: Sustainability sentiment

We first sort returns according to lagged ESG scores in a total of 10 portfolios and value-weight returns. We construct a long-short portfolio strategy that goes long in high ESG firms and short in low ESG firms. We test for sentiment in this portfolio through three measures. In columns (1) to (3) and denoted by 'chneg' we test against the climate news series from Engle et al. (2020), which is either one in case of lots of news on climate cheng and 0 otherwise. Columns (4) to (6) test against the sentiment index by Baker and Wurgler (2006), which is 1 when sentiment is high and 0 otherwise. Finally, column (3) tests against log-changes in the price-dividend ratio as denoted by Robert Schiller. Additionally, we risk-adjust returns under the CAPM, Fama-French three-factor, and Carhart four-factor models. Standard errors are in parenthesis and are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months.

	Dependent variable:								
	LS_t								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
chneg = 1	0.53^{**}	0.72^{***}	0.80^{***}						
	(0.24)	(0.27)	(0.26)						
chneg = 0	0.17	0.06	0.01						
	(0.14)	(0.14)	(0.16)						
perp = 0				0.25	0.26	0.29^{*}			
				(0.21)	(0.16)	(0.17)			
perp = 1				0.02	0.001	-0.04			
				(0.22)	(0.19)	(0.20)			
Δ pd							-0.23^{**}	-0.23^{**}	-0.21^{**}
							(0.10)	(0.09)	(0.10)
mkt - rf	-0.29^{***}	-0.15^{**}	-0.12^{**}	-0.31^{***}	-0.17^{***}	-0.15^{***}	-0.24^{***}	-0.10	-0.10
	(0.05)	(0.06)	(0.06)	(0.04)	(0.05)	(0.05)	(0.06)	(0.06)	(0.06)
smb		-0.57^{***}	-0.57^{***}		-0.50^{***}	-0.50^{***}		-0.49^{***}	-0.50^{***}
		(0.09)	(0.08)		(0.07)	(0.07)		(0.07)	(0.07)
hml		-0.04	-0.003		-0.09	-0.06		-0.10	-0.08
		(0.09)	(0.09)		(0.08)	(0.08)		(0.08)	(0.08)
mom			0.07^{***}			0.05			0.03
			(0.03)			(0.03)			(0.03)
α							0.08	0.07	0.07
							(0.13)	(0.11)	(0.12)
Observations	109	109	109	180	180	180	179	179	179
R^2	0.26	0.50	0.52	0.25	0.46	0.46	0.26	0.47	0.47

Note: $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

ESG and market value

In this subsection of the appendix, we show results of a double-sort on ESG and size.

Table IA.5: Double-sort on size and ESG

We first sort firms according to lagged ESG scores in a total of four portfolios. In a next step, we conditionally sort firms according to their one-month lagged market values and assign them into another four portfolios, ending up with a total of 16 portfolios, which we value-weight with the previous month's market values. We run regressions according to the CAPM and Carhart 4-Factor (excluding the SMB factor) models and document alphas as well as relevant t-test statistics. Bold numbers represent statistical significance at a level of 10% or below. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months.

	ESG$_{t-1}$ low	2	3	ESG$_{t-1}$ high	LS
Panel A: CAPM					
Market Value low	0.531	0.303	0.287	**0.553**	0.022
t-stat	1.332	1.005	1.428	2.85	0.066
Q2	-0.033	0.099	-0.03	**0.301**	**0.334**
t-stat	-0.219	0.663	-0.301	2.723	2.398
Q3	0.023	**-0.206**	0.03	0.132	0.109
t-stat	0.2	-1.791	0.24	1.562	0.822
Market Value high	-0.083	0.009	-0.079	-0.039	0.045
t-stat	-0.593	0.073	-1.006	-0.545	0.267
LS	-0.614	-0.294	-0.366	**-0.592**	0.022
t-stat	-1.211	-0.75	-1.571	-2.491	0.05
Panel B: Carhart (excl. SMB)					
Market Value low	**0.718**	**0.434**	**0.397**	**0.63**	-0.087
t-stat	2.133	1.768	2.585	3.597	-0.281
Q2	0.013	0.158	-0.007	**0.337**	**0.324**
t-stat	0.089	1.255	-0.075	3.303	2.269
Q3	0.027	**-0.211**	0.044	0.136	0.109
t-stat	0.235	-1.851	0.351	1.572	0.801
Market Value high	-0.11	-0.004	-0.077	-0.041	0.069
t-stat	-0.807	-0.032	-1.038	-0.576	0.413
LS	**-0.827**	-0.438	-0.474	-0.671	0.156
t-stat	-1.93	-1.291	-2.502	-3.028	0.387

Ownership concentration, ESG and returns

In this appendix, we show results of a double-sort on ESG and ownership concentration as defined by the Herfindahl–Hirschman Index (HHI). We do not find an ESG premium when controling for HHI as documentd in Table IA.6.

Table IA.6: Double-sort on ESG and ownership concentration

We first sort returns according to lagged ESG scores in a total of four portfolios. In a next step, we conditionally sort returns according to their previous quarter's ownership concentration (HHI) and assign them into another four portfolios, ending up with a total of 16 portfolios, which we value-weight. LS is the abnormal return from a long-short strategy which goes long in high ESG and short in low ESG firms or long in the highly concentrated firms and short in the less concentrated firms, respectively. We value-weight portfolios with the previous month's market values. Finally, we risk-adjust portfolio returns according to the CAPM and Carhart four-factor models and document alphas as well as relevant t-test statistics. Bold numbers represent statistical significance at a level of 10% or below. Standard errors are adjusted for heteroskedasticity and autocorrelation using Newey and West (1987) with a lag length of 12 months.

	ESG low	Q2	Q3	ESG high	LS
Panel A: CAPM					
HHI low	-0.204	0.079	**-0.247**	-0.26	-0.056
t-stat	-0.871	0.562	-1.917	-1.386	-0.273
2	0.166	-0.104	0.028	**0.255**	0.089
t-stat	0.726	-0.76	0.201	1.751	0.516
3	0.019	0.056	0.046	-0.01	-0.029
t-stat	0.147	0.317	0.34	-0.099	-0.158
HHI high	0.033	-0.052	-0.089	0.023	-0.009
t-stat	0.21	-0.542	-0.93	0.244	-0.06
LS	0.237	-0.131	0.157	0.283	0.046
t-stat	0.974	-0.755	1.1	1.344	0.189
Panel B: Carhart					
HHI low	-0.181	0.088	**-0.216**	-0.209	-0.028
t-stat	-0.686	0.573	-1.682	-1.214	-0.137
2	0.157	-0.099	0.01	**0.283**	0.126
t-stat	0.824	-0.658	0.072	1.703	0.762
3	0.022	0.057	0.058	0.007	-0.014
t-stat	0.176	0.332	0.482	0.081	-0.087
HHI high	-0.018	-0.057	-0.079	0.008	0.026
t-stat	-0.118	-0.608	-0.794	0.092	0.149
LS	0.163	-0.145	0.138	0.217	0.054
t-stat	0.68	-0.796	0.908	1.005	0.227

Chapter 2

The Bigger the Better?

Abstract

I empirically investigate wind energy production dynamics and correlations to electricity prices on a turbine-individual level. I find that energy output by large turbines compared to small turbines is higher, less volatile, and correlates less negatively to electricity prices, which allows large turbines to yield a higher average price per production unit. Additional tests on high-frequency data confirm this and indicate that the impact on returns by negative correlations between energy production and electricity prices is large when considering short-term dynamics. These findings are important for investors to consider when allocating capital to alternative venues as renewable energy.

I thank Ken Bechmann, Lars Christian Gaarn-Larsen, Arthur van Benthem, Erik Gilje, Stein-Erik Fleten (discussant) and the conference participants of the 4^{th} Commodity Markets Winter Workshop at Université Laval, the EFA Doctoral Workshop 2019 at Nova SBE and the Commodity and Energy Markets Association (CEMA) Annual Meeting 2020-2021 at Universidad Carlos III de Madrid for helpful comments and discussions. I gratefully acknowledge support from Innovationsfonden and the Pension Research Center. All mistakes are mine.

"As yet the wind is an untamed, unharnessed force, and quite possibly one of the greatest discoveries hereafter to be made will be the taming and harnessing of it."

Abraham Lincoln, 1860

1 Introduction

This paper analyzes wind energy production dynamics and correlations to electricity prices. I utilize a comprehensive data sample by the Danish Ministry of Energy on wind turbines and production outputs and merge it with relevant electricity spot prices to empirically estimate correlations and their consequences on investors' aggregated cash flows. Specifically, I subdivide the data sample according to capacity levels to filter out differences between turbines of different sizes and with regards to production dynamics and important performance parameters. The findings are relevant for investors to consider in the evaluation process of long-term projects in wind energy or other renewable energy technologies.

Investors allocate substantial capital in alternative assets to flee low-interest rate environments, increase diversification and meet investors' demands for more sustainability.[1] One such asset class is investments in renewable energy projects as wind, solar or biomass facilities. In particular in Europe, these investment vehicles gain momentum due to public commitments towards more sustainability in energy production and accompanying subsidy schemes. Governments across Europe incentivize private capital to flow into renewable energy projects to help them meet their commitments from international agreements as the Paris Climate Agreement or Kyoto Protocol. They offer the opportunity to produce cleaner energy and represent a large fraction of today's infrastructure investments.

Investors who consider or are already allocating capital to the renewable energy space face the challenge to fully understand and quantify the risk factors they are exposed to and what they mean in risk-return trade-offs. Furthermore, (often new) regulation for alternatives requires investors to give account to supervisory authorities and other stakeholders. This study adds to this increasing demand and sheds more light on risks and opportunities of wind energy investments with a focus on cash flow implications arising from the dynamics of and correlations between production and electricity prices.

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[1] We can observe an increase in sustainability concerns in the allocation of capital. Investors increasingly consider non-monetary criteria as high Environmental, Social and Governance (ESG) standards, see, for example, Hartzmark and Sussman (2019), Pástor et al. (2021) or Starks et al. (2017). Renewable energy investments represent a popular asset class in this transition of investor preferences, in particular when considering long-term capital commitments. Insurance & Pension Denmark (IPD) estimates that Danish pension funds have invested more than Euro 16 billion in green activities and expect their exposure to increase to more than Euro 46 billion by 2030. Here, green activities are primarily referred to as renewable energy investments and green bonds.

Denmark has been a front-runner in wind energy from its early beginnings.[2] Today, Denmark has a well-established, long-existing (relative to other countries) and transparent wind energy industry, making it a great source for research. Because of the fact that Denmark is so developed in the renewable energy space, findings from this study are highly relevent for other countries, who pursue similar paths and commit to increased sustainability in electricity production.

Investors in wind energy yield cash flows or returns, respectively, from the production and sale of electricity and hence, the primary channels for success are production numbers as well as the level of electricity prices. A third channel is the co-movement of the two, a vital determinant for expected returns. If, for example, investors neglect potentially negative correlations between production and electricity prices, they will overestimate future cash flows and hence, possibly overvalue investment opportunities.[3] The key objective of this study is to investigate this interrelation and enhance on the understanding of its implications. Indeed, the findings show that the relationship between production and electricity prices have real effects on returns, and its economic implications can be large.

In particular, I utilize a unique data sample from the Danish Energy Agency that documents a large fraction of wind turbines and production data in Denmark over the past 17 years, see Figure 1. I distinguish between turbines of different capacity levels and filter out differences in the co-movements of production and electricity prices. The findings provide a greater understanding on the risk exposure of renewable energy entities with respect to production and electricity prices across turbines. In particular, I show that large turbines produce more stable over time and the correlation between power outputs and electricity prices is less negative in comparison to what I observe for their smaller peers. This finding is important, because it helps investors make more informed decisions when allocating capital to alternative venues as energy infrastructure.

The data sample incorporates information on production, capacity levels, vintage years, and locations (latitude and longitude) of wind turbines in Denmark. Merged with the relevant electricity prices from the respective area, obtained from Nord Pool AS, the data provides the opportunity to examine the key objective of this study. That is, I am able to subdivide turbines into different capacity level buckets and determine whether there are differences in the behavior of differently

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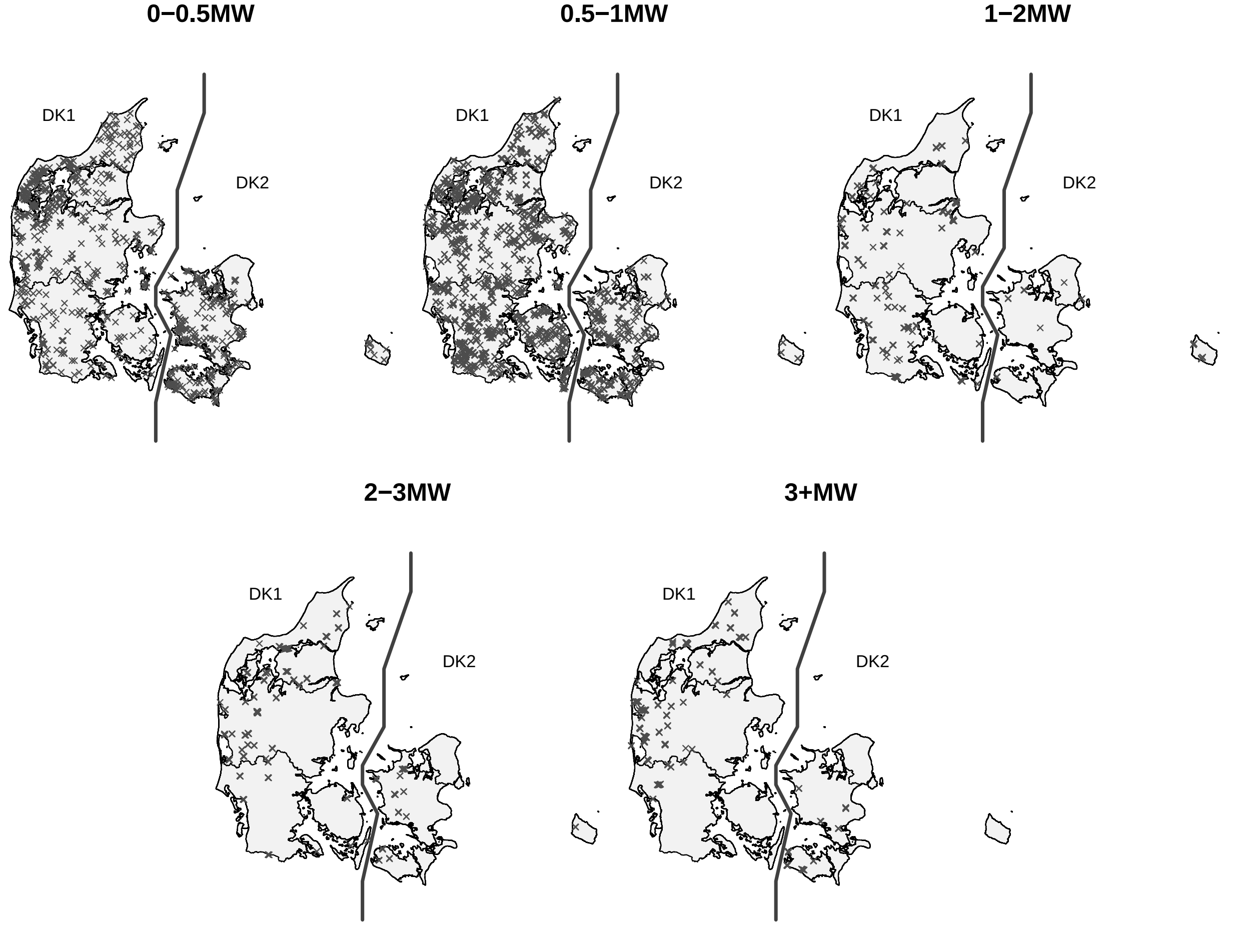
[2] Over the last two decades, Denmark has put large efforts into an energy transition from heavily depending on conventional sources to a much more sustainable approach, including investments into wind-, solar-, or even bioenergy. Today, Denmark produces approximately 30% of all energy through renewable sources and committed to a fully sustainable energy system without any additional substitution from fossil fuels by 2050, see The Ministry of Foreign Affairs of Denmark. Denmark was also one of the first countries to start developing wind energy on a larger scale after the oil crisis of 1973. The first turbine was developed in 1979 and shortly after MHI Vestas and Siemens Gamesa were founded.

[3] For example, it is a well-documented that in California many solar-energy projects produce lots of electricity throughout the day and little during the night when electricity demand peaks; a phenomenon commonly referred to as the 'duck-curve.' Resulting price impacts are significant and leads to a situation where prices are low during the day due to high supply and high at night when supply is much lower and demand peaks, see greentechmedia.

Figure 1: Denmark's turbines by capacity

This figure provides an overview of all on-shore wind energy turbines in Denmark in the data sample that contain production data. Not all turbines are still in use today. In particular, the figure shows turbines according to their individual capacity level. Electricity prices differ according to their price area DK1 or DK2. *Source:* Own representation and based on data from the Danish Energy Agency.



0–0.5MW

0.5–1MW

1–2MW

2–3MW

3+MW

large turbines.

I further utilize high-frequency data from a private equity investor that invests into renewable energy projects. In particular, I have access to information on a total of 81 turbines across Denmark, which, next to basic technical specifications, incorporates production outputs as well as wind speeds. I am therefore able to compare my results based on monthly observations against those coming from more granular data.

I make three hypotheses. First, I expect large turbines to produce more per capacity level as their greater altitude exposes them to more constant wind speeds. Second, I expect a significant negative correlation between wind energy production and energy prices. This leads to a situation in which the yielded price of electricity by wind projects is below the average price in the same time horizon. Third, I expect the size of turbines to be irrelevant with respect to the magnitude of correlation between energy outputs and electricity prices. This means that regardless of the capacity level of turbines, they are, on average, equally negatively correlated to electricity prices and yield similar returns.

The structure of this study is as follows. After a literature review, I exhibit the dataset in a descriptive manner in Section 2. Section 3 elaborates on the methodology applied to the analysis. Section 4 shows the results. Section 5 compares results to those obtained from high-frequency data. Section 6 discusses the findings and Section 7 concludes the paper.

Related literature

There are two approaches concerning the investigation of the relationship between the renewable energy production and electricity prices. One is referred to as simulation based and whereas the other is empirical. Simulation-based studies root in models that mostly utilize both real and hypothetical data to determine price effects of correlations. Empirical studies, on the other hand, rely on real (past) data only and apply econometric analyses (Würzburg et al., 2013). This study relies on an empirical application and adds to this stream of literature.

A related and empirically-based study is, for example, Jónsson et al. (2010), which looks at wind power forecasts and electricity prices in Western Denmark. They find a strong negative correlation between the two variables and show that wind power forecasts have distributional consequences for prices under varying scenarios. They distinguish between different times of wind power penetration and find that the higher wind power forecasts, the more severe the downward pressure on electricity prices. Other applications with similar results for the German and Spanish markets are documented by Neubarth et al. (2006) or Gelabert et al. (2011). They too find strong negative correlations between renewable energy production and electricity prices. Woo et al. (2011) researches the energy market in Texas (USA) based on high-frequency data. They as well find a negative causal effect of wind energy production on electricity prices, ranging from \$0.32 to 1.53\$ for every additional 100-MWh.

Other studies further consider long-term implications from additional renewable energy penetration on electricity prices with sometimes opposing findings. For example, Hindsberger et al. (2003) show that the increase in renewable energy targets as a result of the Kyoto agreement led to a change in consumer electricity prices of between -2 to 18 EUR/MWh in the Baltic Sea Region. Traber and Kemfert (2009) investigate the consequences of German feed-in-tariffs on the electricity market and pin down two opposing effects, the consumer and the producer effect, where it is unclear how the sum of the two play out. Milstein and Tishler (2011) even come to an unexpected result. Conducting a long-term study in the Israeli market, they conclude that electricity prices in fact increase with more renewable energy capacity. Milstein and Tishler (2011) argue that this is mainly due to an inelastic demand curve and the inability of renewable energy to adjust production (in this case photo-voltaic cells).

Energy economics also found its place in the broader finance literature. One area picking up momentum, which partly revolves around renewable energy production dynamics and uncertainties, is the field of weather derivatives. Hain et al. (2018), for example, consider the meaning of wind and solar production volatility from a pure risk perspective, evaluating opportunities to hedge against production volatility. Reviewing the German market, they find that typical plain-vanilla options aiming to hedge production uncertainty are not an efficient tool against fluctuating energy output. However, they do not consider causality or correlation between production and electricity prices.

As weather derivatives allow investors and firms to hedge weather risks, they are not only studied from a micro- and valuation perspective (e.g. Dorfleitner and Wimmer, 2010, Pirrong and Jermakyan, 2008, Svec and Stevenson, 2007, Woodard et al., 2008, Zhu et al., 2018), but also with regards to implications on a firm level. Pérez-González and Yun (2013), for example, look at the introduction of these weather derivatives and investigate effects on firms when utilizing them. This study enhances the understanding of the pricing of these derivatives and is valuable for investors and firms that have large exposure to renewable energy assets and therefore rely on the weather.[4]

My study adds to the current literature and developing research area in a number of ways. The unique data from the Danish Ministry of Energy allows me to study risk and correlation dynamics between production and electricity prices on a turbine-level. Specifically, the distinction by capacity levels and the investigation of economic consequences between differing production profiles, to my knowledge, is novel and the first of its kind in the literature, enhancing the understanding of alternative investments in wind energy. This study is important not only for investors, but also for regulators and countries that aim to achieve the long-term goal of becoming fossil-free. Comprehending the market micro-structure of electricity markets remains a vital challenge in both academia and the industry and the findings of this study add to this discussion.

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[4] In a broader sense, this study further contributes to applied corporate finance and in particular the valuation and project finance literature. Classic theory on valuation as exhibited in textbooks as Trigeorgis (1996), Dixit and Pindyck (1994), Tirole (2010), or Gatti (2013), claims that it is the dynamics and mechanism of expected cash flows, which largely matter for the valuation of projects. Also newer textbooks that solely consider renewable energy investments stress the importance of fully understanding the dynamics of risk-return profiles in long-term energy investments, see Barcelona (2017).

2 Data

I collect data on wind turbines, aggregated energy demand, and electricity prices, all of which I review hereafter. All data is publicly available and can be obtained from the Danish Energy Agency, Energi Data Service and Nord Pool AS.

Turbine data

I obtain turbine data from the Danish Energy Agency. The database records a large fraction of Danish wind turbines and tracks monthly production outputs. Specifically, one can observe the monthly kilowatt production (kWh) for each turbine in the sample. The data sample starts in January 2002 and goes until December 2017. If a turbine was already developed and in operation before January 2002, I cannot observe production outputs from that time. I delete all first month observations from the sample, because new turbines may have only been in operation for a fraction of that particular month, in which case these numbers would not be representative of a full month of production and potentially skew results.

Furthermore, the Danish Energy Agency provides turbine specific information on geographical locations (longitude and latitude data), an on- and off-shore ticker, capacity levels, vintage, rotor diameters, and heights in another data set. The total number of turbines in this sample consists of 6258. In particular, location data will be important in a later step in order to merge production data with the relevant price area.

I merge the data sets of monthly production estimates and turbine specific information according to the individual turbine identification number, referred to as *Modelnummer*. A few turbines (mostly small-capacity turbines) do not exhibit information on production, which I delete from the sample. I focus on on-shore turbines only and exclude all off-shore turbines, because they are exposed to very different environmental conditions and a cross-capacity comparison would not account for such.

This leaves a total of 4,225 turbines with detailed production and turbine specific data. Table 1 details the technical specifications across the sample and according to capacity levels. As in Table 1, I split the data sample according to capacity levels and breaking points of $\{0-0.5, 0.5-1, 1-2, 2-3, 3+\}$MW, which I continue to apply throughout the analysis.

As mentioned, the dataset contains technical and geographical specifications. Figure 1 provides an overview of the turbines' locations and their capacity levels. In general, there are much more low-capacity relative to large-capacity turbines in operation.

Appendix A, Figure A.2 further shows the vintage of turbines in the sample. One can observe that, in particular in the 1990's, many new turbines went into operation. This has several causes,

Table 1: Summary statistics

This table exhibits all turbines in the sample that document production outputs and details on locations. N documents the number of turbines, whereas Avg Capacity (MW), Height (m), and Rotor diameter (m) depict average estimates within each sub-group.

	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
N	4225	1001	2428	287	252	257
Avg Capacity (MW)	0.9	0.2	0.7	1.7	2.7	3.4
Height(m)	47.3	28.7	45.2	62.0	80.7	90.6
Rotor diameter(m)	50.0	25.0	46.4	70.2	94.8	114.9

but first and foremost, it is due to Denmark's commitment to more sustainability in energy production and the resulting, and very profitable subsidy schemes over the last few decades. Figure A.2 further demonstrates that not only in the 1990's but also in the 2010's, Denmark experienced a sharp increase in new turbine development. Surprisingly, in the 2010's when technology was already much more developed, a large number of additional relatively small turbines were built and went into operation.

Figure A.1 shows the distribution over turbines' capacity levels. As mentioned, one can observe that the Danish wind energy market predominantly consists of low-capacity turbines, which are in the $\{0-0.5, 0.5-1\}$MW capacity brackets.

Electricity prices

I obtain monthly average electricity spot price data from Nord Pool AS, a leading European electric power exchange. All prices are day-ahead prices, referred to as *Elspot* prices. There are three electricity spot prices that are of interest for the analysis. Specifically, I observe the SYS, DK1, and DK2 electricity prices. All prices are denominated in Euro per MWh and go from January 2002 until December 2017.

According to ENERGI DATA SERVICE, the system (SYS) electricity spot price is the balanced price on the Nordic electricity market between the areas. It therefore serves as a proxy of the average price in the Nordic market. Though only partly relevant for the analysis, it provides an indication by how much Danish electricity prices co-move with the entire Nordic market.

Denoted as DK1 and DK2, I utilize electricity prices from the two different price areas in Denmark. The western price area (DK1) covers Jutland and Fyn (North, Central, and southern region of Denmark), whereas the eastern price area (DK2) consists of Zealand and the Capital Region. The two price areas each operate their own electricity market and prices between the markets can differ. Each turbine locates in either one of the two areas and is therefore exposed either to the DK1 or the DK2 price.

Figure B.1 in Appendix B shows an overview of the time series. The electricity prices of DK1 and DK2 highly correlate (approximately 0.8 to 0.9, see Table 4), however, in certain periods they differ substantially. Hence, it is of vital importance to assign the right price to each turbine in question, determined by which price area they operate in. To do so, I apply reverse geocoding through Photon[5], assigning area names through latitude and longitude information that is available in the turbine data set. Through the area name I can then assign the relevant DK1 or DK2 electricity price to each turbine in the sample.

Consumption

As part of the empirical analyses, I further use electricity consumption data as a control variable for later regression analyses. I download consumption data from Energistyrelsen, which provides monthly data on the consumption of electricity in Denmark from different sources as well as total estimates. The data exhibits electricity consumption coming from oil, natural gas, coal and coke, waste (non renewable), renewables, electricity import as well as total estimates. Originally, the data exhibits consumption in Terajoule (TJ), which I translate into Terawatt hours (TWh).[6] The data goes from January 2005 until today.

3 Methodology

This chapter outlines the methodology of this study. I first elaborate on production and volatility estimations and then transition over to the calculation and impact assessment of correlations between production and electricity prices.

3.1 Production and volatility

This section concerns the measurement of turbine electricity production and volatility. The driver and development of production volatility almost exclusively relies on the environmental conditions turbines are exposed to.[7] Operators produce more under favorable conditions (i.e. high average wind speeds), and vice versa. Higher production outputs tend to lead to higher revenues, free cash flows, and hence returns.

To compare wind energy turbines in the cross-section, I first scale all production data according to each entity's capacity, as depicted by the amount of megawatts (MW). In every month t, I divide

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[5] Photon is an open source geocoder, which is accessible through a public API and is powered by komoot.

[6] One unit in TJ equals $\frac{5}{18} * 1000^{-1}$ in TWh.

[7] In certain cases, wind energy producers might additionally decide to actively shut down electricity production due to, for example, negative electricity prices or maintenance.

the total output estimate by the capacity level of the turbine through

$$MWh\ of\ Turbine_i\ perMW\ in\ Month_t = \frac{Total\ MWh\ of\ Turbine_i\ in\ Month_t}{Capacity\ in\ MW} \tag{1}$$

I utilize the resulting production estimates over time to obtain averages and volatility estimates across turbines. I further compute total and relative volatility across turbines. Specifically, I condition the cross-sectional data set of averages and volatility estimates according capacity levels from small to large turbines and apply breaking points at $\{0-0.5, 0.5-1, 1-2, 2-3, 3+\}$ megawatts (MW). I then use turbine-individual estimates to obtain average volatilities for turbines of each capacity level.

These estimates quantitatively examine the differences in production outputs of differently large turbines. This is important for investors as it gives them a better understanding of how much turbines produce over time and how large differences are between capacity levels. Also, it lays the groundwork for the subsequent empirical analysis, which investigates how production and electricity prices correlate.

3.2 The relationship between production and electricity prices

The price of electricity is highly volatile and fluctuates heavily according to supply and demand (see Appendix B). Because there are only very limited possibilities of storage, wind energy operators are forced to sell electricity at the spot price if they have not hedged their position with derivatives or, becoming more popular, power purchase agreements (PPA). From an empirical research perspective, this is good news, because one can more precisely observe how much of an impact renewable energy production has on electricity prices as there is little managerial flexibility available to operators.

It means that not only does production volatility in itself have an impact on the economics of a wind energy investment through fluctuating cash flows, but the price investors receive for the commodity of electricity might be related to the production levels themselves. In the renewable energy market and alternative investment industry, there is an increasing concern over the interrelation between electricity spot prices and the level of production, which, as mentioned, roots in the absence of storage opportunities. Operators are forced to deliver their commodity at the time of production and so the average price of electricity might be a misleading source of information for estimating future returns, if in fact production and prices are correlated.[8]

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[8] This is especially a concern for investors intending to enter a new market with a large-scale project. Coming in as a first mover especially bears the risk of underestimating the effect of additional production on electricity prices. This too is one of the reasons for why investors increasingly favor projects that incorporate hedging positions as PPAs.

Investors in wind turbines expect to earn cash flows from the electricity they produce and feed into the grid system. They are compensated for their production outputs with the according electricity price at time t.[9]

$$C_t = MWh_t \times P_t \tag{2}$$

Looking at this very intuitive relationship might make it tempting for investors to simply consider average electricity prices and production levels to forecast cash flows in the future and assess their investment opportunity. However, this approach only holds true if and only if $\rho(MWh_t, P_t) = 0$. If this relationship does not hold true and $\rho(MWh_t, P_t) \neq 0$, investors might either over- or underestimate future cash flows. The analysis of this very relationship between prices and production and its monetary implications depicts the key objective of this paper.

Table 2 presents a simple example on how negative correlation of $\rho(MWh_t, P_t) < 0$ matters for investors. The example assumes an arbitrary production output of a turbine at a given electricity price over two periods, $t = 1$ and $t = 2$. At $t = 1$, the electricity price is 10EUR/MWh and at $t = 2$ it is 20EUR/MWh. An investor's turbine produces 40MWh at $t = 1$ and 10MWh at $t = 2$. The investor's cash flows are going to be EUR 400 and EUR 200 at time $t = 1$ and $t = 2$, respectively. This yields in an average cash flow of EUR 300 for every day that he holds his investment. If the investor would have just considered an average price over time and multiplied such with average production over time, the investor would have expected EUR 375 per day on average or 2 days × EUR 375 = EUR 750 in total. However, his actual earnings are EUR 400 + EUR 200 = EUR 600 in total. The average price of electricity that he would receive for every MWh he produces would therefore be $\frac{300}{\frac{1}{2}(40+10)}$ = EUR 12, which is significantly lower than EUR 15 ($\frac{10+20}{2}$). Here, the deviation from the average price as denoted by $\Delta\overline{P}$ equates to $\frac{12-15}{15} = -20\%$.

To test whether we see this phenomena in the data and determine if there are differences between capacity levels, I calculate the delta between average and realized prices investors earn for their investments. I do so according to the example described in Table 2 or specifically through

$$\Delta\overline{P_i} = \frac{1}{n}\sum_{t=1}^{n} \frac{P_{i,t}}{\overline{P}} \frac{MWh_{i,t}}{\overline{MWh_i}} - 1, \tag{3}$$

where $\Delta\overline{P_i}$ is the difference from the average electricity price turbine i is exposed to. If turbine i receives exactly the average electricity price, then $\Delta\overline{P_i} \overset{!}{=} 0$. I calculate $\Delta\overline{P_i}$ for every turbine in the sample and interpret the resulting distributions. I am interested in two questions. First, does the average $\Delta\overline{P}$ for each capacity level significantly differ from 0 and second, do the distributions

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[9] See Figure C.3 in Appendix C plots the distribution of average monthly cash flows computed through this equation for all capacity brackets.

Table 2: Cash flows under negative correlation between prices and production

This table provides an example of how investors are at risk to overestimate cash flows when prices and production are negatively correlated. In particular, the correlation between the variables of prices (EUR/MWh) production (MWh) in this example is $\rho < 0$.

	day	EUR/MWh		MWh				Cash Flow
	1	10		40				400
	2	20		10				200
Average per day		15	x	25	=	375	$\neq$	300

differ across capacity levels?

Finally, I distinguish between high and low production times. I consider the highest and lowest 20% of production data points and determine what price level an investor receives in comparison to the average price over the entire time horizon of the particular turbine. I calculate

$$\Delta\overline{P_i} = \frac{1}{\sum_{t=1}^{n} N_{i,t}} \sum_{t=1}^{n} \frac{P_{i,t}}{\overline{P}} N_{i,t} - 1, \tag{4}$$

where

$$N_{i,t} = \begin{cases} 1 & \text{if } MWh_{i,t} \text{ in top (alternative bottom) 20\%} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

It is important to note that $\sum_{t=1}^{n} N_{i,t}$ differs across two turbines if they do not have equally many data points available over time. For example, one turbine might have been in operation for a longer time than another. As previously, I compute $\Delta\overline{P}$ through the average across all turbines in a given capacity level. As robustness checks, I also run the analysis with alternating top and bottom brackets. In particular, I consider top and bottom production times of 10 to 30%.

3.3 Production and electricity prices in a regression framework

The previous section outlines an approach that compares and assesses monetary implications of correlations between production outputs and relevant electricity spot prices. To further examine the co-movement of the two financial performance drivers and control for other factors, I apply a panel-regression approach to the data. This chapter documents this approach and which variables it controls for.

My regression framework is similar to the work of Woo et al. (2011). Specifically, I run the panel regression of

$$p_{i,t} = \alpha + \beta GWh_{i,t} + \gamma p_{i,t-1} + \kappa TWh_t + \sum_{j=1}^{11} \mu_j M_{j,t} + \epsilon_{i,t}, \tag{6}$$

where $p_{i,t}$ is the monthly log-price of electricity that the turbine i is assigned to (DK1 or DK2) and $GWh_{i,t}$ depicts the production of an individual turbine, both at time t. Please note that I use gigawatt hours (GWh) instead of megawatt hours (MWh), the simple reason being to increase coefficients in their magnitude and make them more readable.[10] Moreover, $p_{i,t-1}$ depicts the lagged monthly log-price of electricity. The coefficient of α exhibits the constant of the regression, whereas $\epsilon_{i,t}$ is the error term for turbine i at time t. The variables of TWh_t depicts the monthly electricity consumption in Denmark at time t and denoted in terawatt hours (TWh). I further adjust for month-fixed effects through $M_{j,t}$ and thereby account for cyclical price and production levels throughout the year.[11] It is important to account for month fixed effects, because electricity prices usually to follow a strict seasonal pattern, in which prices tend to be higher during winter and lower during summer, see, for example, Escribano et al. (2011), Lucia and Schwartz (2002), or Seifert and Uhrig-Homburg (2007). Finally, I cluster standard errors by time.

I run three additional regression specifications as robustness checks to address econometric concerns and determine the magnitude of coefficients. First, I run regressions on the deltas of prices against deltas in production and consumption to address potential stationarity issues. Secondly, I run a log-log regression to determine relative changes. Third, I run regressions on real prices. Furthermore, I run rolling regressions to investigate whether the exposure of production to electricity prices changes over time as well as individual turbine-level regressions, in which I consider the resulting distributions of β-coefficients.

As in the previous chapter, I am predominantly interested in the following questions. First, is there significant correlation between wind energy production and electricity prices and if so, how does it matter for investors? Second, are there differences in the correlation estimates between differently large turbines? Are differently large turbines exposed to varying marginal price changes?

4 Empirical Analysis

This section documents the empirical results. As mentioned, I generally split the data sample on wind turbines according to capacity levels. Breaking points are at $\{0-0.5, 0.5-1, 1-2, 2-3, 3+\}$MW. Also, it is important to recall that I adjusted production level data according to

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[10] One gigawatt hour (GWh) equates to 1000 megawatt hours (MWh). One could also interpret the results as the coefficient being multiplied by a factor of 1000. The significance takes no effect in that scaling.

[11] This means that $M_{j,t} = 1$ in January if $j = 1$, in February if $j = 2$, until November if $j = 11$. Otherwise $M_{j,t}$ is zero.

Equation (1), which makes data between capacity levels directly comparable.[12]

First, I analyze summary statistics of the sample, providing an understanding on how differently sized turbines compare to each other with regards to production outputs only. Second, I elaborate on the analysis of production versus electricity prices with the goal to determine correlations between these two drivers of cash flows and its financial implications.

4.1 Summary statistics

This section outlines stylized facts about the turbine data sample. As shown in Table 1, there are more low-capacity than there are high-capacity turbines, which is important when interpreting the results not only in this section but in the ensuing analysis also. Furthermore, the summary statistics section outlines important facts regarding electricity prices.

Turbine production

There are presumably several reasons for the vast number of low capacity turbines. First, technology was not as advanced a few decades back and low capacity turbines today were considered state of the art back then. Technological advancements over time allowed investors to increase capacity and productivity levels.[13] Second, it might very well be the case for some investors that they find lower-capacity turbines easier to develop, potentially due to less risk before and during construction. Another and rather practical intuition might be that the process of re-powering[14] is easier when replacing small-level turbines that are already largely in place with similar types as permits for that specific type are already obtained.[15]

Appendix A.2 documents the number of new turbines according to vintage and capacity levels. Until the early 2000's, it was mostly (very) small turbines in operation. Only later, technology improved and developers increasingly built large-scale turbines. Nevertheless, also small-scale turbines (0-0.5MW) were kept being developed to a large degree in the 2010's (perhaps many of those built in the 1980's and 1990's were re-powered as mentioned).

Table 3 documents monthly average production and volatility estimates of turbines in the sample and across price regions (DK1 and DK2). Production estimates are adjusted according to Equation (1), so that the relative turbine performance is directly comparable.

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[12] It hypothetically assumes that every turbine in the sample has a capacity of 1MW with respect to their production output.

[13] See the U.S. Department of Energy.

[14] Replacing old with new turbines.

[15] In practice, investors would often buy old wind farms not to keep producing electricity with the turbines in place but instead to replace (re-power) the old turbines with new ones. They strip down old turbines, sell them for their scrap value, and develop the farm from scratch. That way, investors forgo the risk of not receiving required permits or not fulfilling other regulatory necessities.

Table 3: Production and volatility

The table sows monthly average production and volatility estimates of wind energy turbines according to their capacity levels and across regions. The western price area (DK1) covers the north, central, and southern region of Denmark (Jutland and Fyn), whereas the eastern (DK2) price area consists of Zealand and the Capital Region. $\overline{MWh}$ averages across mean production estimates on a turbine level over time. The standard deviation of $\overline{\sigma}_{MWh}$ computes the average of volatility estimates of individual turbine-level production volatility. Production share (in %) documents production hours as a share of the total production hours within each category. Capacity share (in %) documents capacity levels as a share of total capacity within each category. N is the number of turbines in each bracket.

	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
Total						
N	4225	1001	2428	287	252	257
$\overline{MWh}$	168.8	144	159.4	186.1	231.4	273.3
$\overline{\sigma}_{MWh}$	61.7	60.2	59.6	64.3	70.6	76.4
Production share	100	23.1	64.5	6.4	3.7	2.3
Capacity share	100	5.6	43.3	12.1	16.9	22.1
North Denmark Region						
N	986	279	518	47	68	74
$\overline{MWh}$	181.7	159.8	168.7	218.5	240.1	277.7
$\overline{\sigma}_{MWh}$	62.7	60.2	60.2	70.7	72	77.4
Production share	100	29.5	58.6	5	4.8	2.2
Capacity share	100	7.1	39.1	8.9	18.7	26.1
Central Denmark Region						
N	1271	265	677	104	106	119
$\overline{MWh}$	175.5	143.9	159.3	202.2	226.6	268.9
$\overline{\sigma}_{MWh}$	61.5	59.9	58.4	65.5	66.4	74.7
Production share	100	20.9	62	7.5	4.5	5.1
Capacity share	100	3.6	35	12.9	20.2	28.3
Region of Southern Denmark						
N	1091	139	792	104	32	24
$\overline{MWh}$	158.6	137.3	157.8	153.3	215.6	254
$\overline{\sigma}_{MWh}$	60.5	61.6	60.1	58.2	71.1	63.8
Production share	100	11.3	77.7	8.4	2	0.6
Capacity share	100	3	60.9	17.2	9.4	9.5
Capital Region of Denmark						
N	85	30	34	18	3	
$\overline{MWh}$	155.7	122.2	147.7	201.7	305.4	
$\overline{\sigma}_{MWh}$	68.1	72.2	59.1	75.6	83.8	
Production share	100	30.2	44.5	24.1	1.2	
Capacity share	100	8.2	35.4	45.8	10.6	
Region Zealand						
N	792	288	407	14	43	40
$\overline{MWh}$	157.6	134.3	151.9	180.5	236	289.7
$\overline{\sigma}_{MWh}$	61.6	58.4	59.6	65.5	77.2	87.2
Production share	100	34.7	58.9	1.7	3.8	0.9
Capacity share	100	11.2	43.7	4.2	18.6	22.3

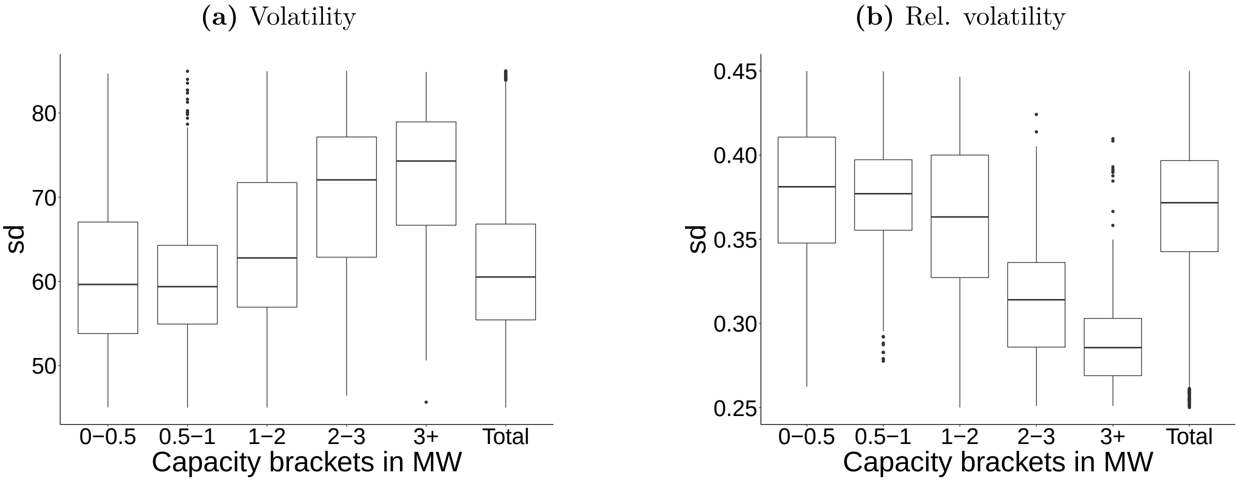
Table 3 shows that the most efficient entities, measured in average monthly production outputs per MW in capacity, are very large turbines. Overall, productivity monotonically increases from small to large turbines. Table 3 further shows average standard deviations of outputs over time

($\overline{\sigma}_{MWh}$). Absolute volatility tends to increase over capacity levels and production outputs, though the trend is not always as clear.

To further investigate distributional properties of electricity outputs, Figure 2 shows boxplots on production volatility. Figure 2a confirms that, on average, absolute volatility in monthly production outputs by large turbines is higher as compared to smaller ones (measured in absolute MWh). The sub-group of 3+MW is about 16MWh more volatile than the smaller peers in the 0-0.5MW group.[16]

Figure 2: Volatility in turbine production

Figures 2a and 2b show boxplots of volatilities across wind turbines. Volatility is derived from monthly production data on an individual turbine level, where MWh-outputs are adjusted according to capactity levels, see Equation (1). There are observations outside the boundary of the plot, but were excluded to visualize the differences between the main bulks of the distributions. The horizontal line in each box represents the median.


(a) Volatility

(b) Rel. volatility

However, looking at relative volatility in Figure 2b, larger turbines tend to be less volatile than smaller ones. On a median level, production outputs vary 4-9% less in the highest-capacity bracket, meaning that over time, large turbines produce more steadily than their smaller peers. It seems as if there is a breaking-point after 2MW in capacity as this is where relative volatility decreases significantly. This suggests that at this capacity level (2MW), turbines operate in an altitude that, by nature, is exposed to more consistent wind speeds, or put differently, turbines

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[16] Absolute volatility differences, by nature, are much greater when not considering capacity level adjustments. For example, volatility in the 3+MW capacity bracket suggest that a 3.5MW turbine exhibits a total monthly production volatility (median) of approximately $3.5 \times 74 = 267.257$ MWh. If one wanted to compare absolute volatility differences between two different turbines, then the differential between capacity levels needs to be re-adjusted for. For example, assume a 1MW turbine with an absolute volatility of 60MWh and a 3MW turbine with a 80MWh volatility, then the absolute volatility difference is $3 \times 80 - 1 \times 60 = 240 - 60 = 180$MWh.

grasp more steady wind, and therefore produce with higher persistence.

Production volatility is important to investors, because more stability in production means higher certainty and predictability in performance. Considering no correlations at this point, it would also smooth cash flows over time. This observation has important implications. Essentially, less variation in cash flows over time means more performance predictability, less risk, and therefore higher risk-adjusted returns. In equilibrium, investors should be willing to pay higher prices for assets with these features.

Furthermore, more stable cash flows also have important implications for the financing structures of projects. Under the assumption of less volatility in future expectations of cash flows, investors might be able to take on more debt and thereby boost their expected return on equity. Just considering these summary statistics and all else equal, large (preferably very large) turbines clearly outperform their smaller counterparts. They produce more on average and are less volatile in their output dynamics.

Finally, Table 3 documents production and capacity shares within the sub-groups. I show that small turbines make up the largest share of production hours in the sample. Specifically, it is the 0-0.5MW turbines that account for close to 60% of the observed production. When considering the capacity shares of each subgroup, I find that larger turbines represent a much greater fraction of total MWs of the total sample. This indicates that even though market shares as of today are more evenly distributed among capacity levels, the sample's observations largely originate from small turbines due to the fact that many larger turbines started operation only in the end of the sample's time horizon.[17] This observation is important to consider as it might have implications for the persistence of the presented empirical findings in the future.

Electricity prices

Wind turbines yield income through selling their production outputs of electricity. If a turbine is fully merchant, it yields the current price of electricity that is traded on the spot market. This section reviews the two relevant spot prices in Denmark. As outlined in the data section, Denmark is split into two electricity grid areas. The western grid area depicts the DK1 price area and covers the north, southern and central regions (Jutland and Fyn). The eastern part of the country is referred to as the DK2 price area and consists of Zealand an the Capital Region. This section documents stylized facts on the two price areas and how they interact.

Table 4 reports the differences in the time series data of the two price areas DK1 and DK2 from January 2002 until December 2017. I find that there are significant differences between the mean

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[17] See Figure A.2 in Appendix A.

and standard deviation. Overall, the DK1 price area exhibits a lower average price accompanied by lower volatility. There is no significant difference in the median. The two time series further yield a correlation estimate of 0.875.

Table 4: Summary statistics of electricity price areas

This table shows the summary statistics of the price areas DK1 and DK2. Numbers are in EUR per MWh. The monthly price data was obtained from Nord Pool AS and goes from January 2002 until December 2017. The variables of $\overline{P}$, $\tilde{P}$, $\overline{\sigma}_P$, and $\rho(P_{DK1}, P_{DK2})$ document the average price, median, standard deviation, and correlation of prices. I further document differences and respective significance levels in these differences. Specifically, the Mood's median test evaluates differences in the median. The test for differences in standard deviations is conducted through an F-test of the ratio of variances. A star as denoted by * depicts statistical significance to a level of $p < 0.01$.

	DK1		DK2	diff
$\overline{P}$	35.905		37.962	-2.057*
$\tilde{P}$	34.550		34.645	-0.095
$\overline{\sigma}_P$	10.630		13.028	-2.398*
$\rho(P_{DK1}, P_{DK2})$		0.875*		

The comparison of the two price areas of DK1 and DK2 shows that the two time series co-move to a high degree.[18] Also, the time series of prices are subject to high volatility and prone to jumps. At the same time, sometimes significant differences between the two price areas underline the importance of considering the relevant price area for each turbine when conducting the empirical analysis. This is especially relevant considering times during which the two prices can deviate by up to 20 or EUR/MWh or more, see Figure B.1b in Appendix B.

4.2 Production and electricity price impacts

This section extends the previous section's results and can be considered a second channel for the profitability of energy production through wind turbines. Specifically, it considers the dynamics of Equation (2) with regards to production and electricity prices. The empirical results shed more light on how correlation between these two drivers of cash flows matters for investors.

Figure C.3 in Appendix C shows the distributions of cash flows according to Equation (2) and across capacity levels. Each turbine is matched with the price area they are located in (DK1 or DK2) and monthly production outputs per MW in capacity is multiplied with the respective average price in that particular month. The figure confirms the previous observations with regards to production level data across capacity levels. Investors seem to earn similar cash flows per MW

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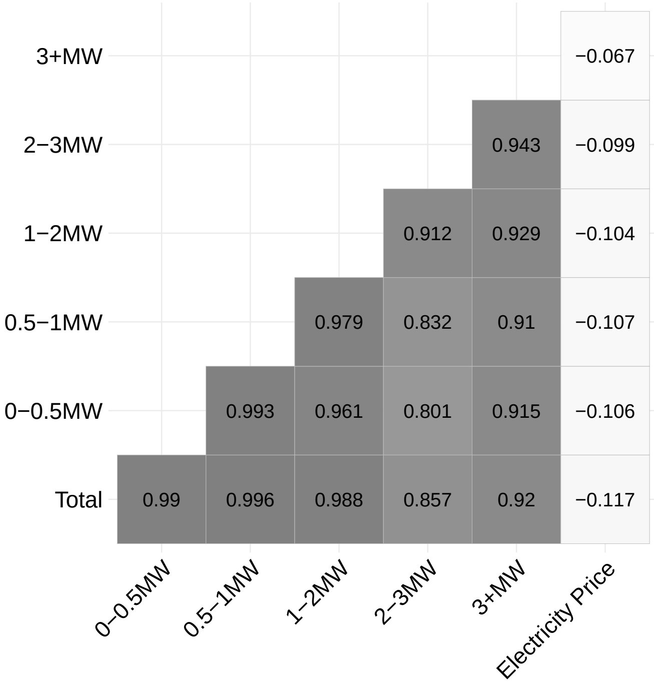
[18] See Appendix B, Figure B.1a and B.1b for an exhibition of the time series of the two price areas.

in capacities of $\{0-0.5, 0.5-1, 1-2\}$MW, whereas cash flows are higher in the very high-capacity levels of $\{2-3, 3+\}$MW. The primary channel for this observation is higher production outputs by larger turbines. The second channel roots in the correlation between production and electricity prices as examined in the remaining empirical analysis.

First, I calculate simple correlations between production and electricity prices. To compute correlation coefficients across capacity levels, I estimate average production outputs over time within capacity levels and across turbines. To determine correlation estimates between production and electricity prices, I take into account individual production estimates of every turbine in each capacity level and the relevant price (DK1 or DK2) of the given turbine in a panel-data set. Figure 3 shows the results.

Figure 3: Correlations between turbine production and electricity spot prices

This figure shows correlation estimates between turbine production of different capacity levels as well as turbine production and electricity prices. To compute correlations between capacity levels, I calculate average production levels in each capacity bracket. Correlations between electricity prices and production I compute from panel-data on individual turbines and relevant price area data. All estimates are significant to the highest level ($p < 0.01$).



As mentioned, negative correlations between power production and electricity prices have an impact on cash flows because they determine the average electricity price the asset is exposed to (see Table 2 for an example).[19] The more negative the correlation estimate, the lower the average

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[19] In the industry, this is sometimes also referred to as the capture price.

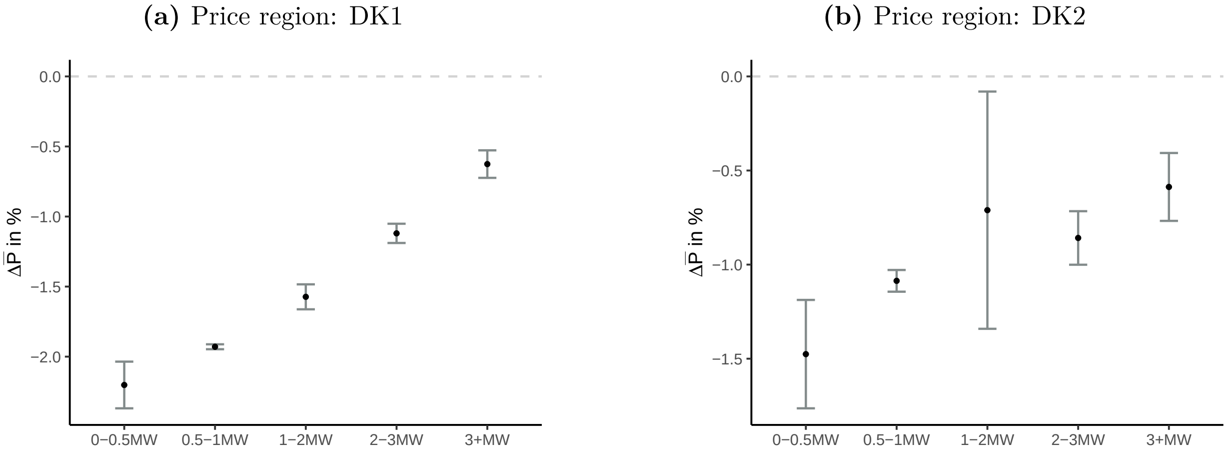
price I yield as an investor, translating into lower cash flows in total.

Figure 3 presents two major findings. First, electricity production across wind turbines highly correlates. Nevertheless, correlation generally decreases when the gap between capacity levels widens. Second, production level data across all capacity levels is negatively correlated with electricity prices. Absolute correlation decreases slightly in the 2-3MW bracket and even more so in the highest bracket of 3+MW.

To see, if this negative correlation observation indeed has implications on the average electricity price wind turbines are exposed to (i.e. capture price), I calculate the deviation from the average price ($\Delta\overline{P}_i$) for each turbine according to Equation (3). I obtain distributions of $\Delta\overline{P}$ for every chosen capacity level. Figure 4 shows the results.[20]

Figure 4: Production vs. prices

I calculate price deviations from the average electricity price for every turbine and according to the price areas DK1 and DK2, see Equation (3). I show the distributions of $\Delta\overline{P}$ according to capacity levels. Black points in the graph depict averages and the error bars are 95%-confidence intervals.



(a) Price region: DK1

(b) Price region: DK2

Figure 4 shows negative average values (black dots) for $\Delta\overline{P}$ on a significant level for all capacity levels, suggesting that owners of turbines receive less than the average price of electricity over time. For example, small turbines in the 0-0.5MW bracket in the DK1 price area exhibit a $\Delta\overline{P}$ of a little less than -2%, meaning that for the produced electricity they receive a price, which is -2% lower than the average when they sell it in the market.[21]

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[20] In Table B.1 of Appendix B, I document additional test statistics on whether the differences across $\Delta\overline{P}$ estimates are significantly different from zero.

[21] Assume this practical example: The average electricity price is EUR 30 per MWh for a given time horizon. The owner of a turbine with a $\Delta\overline{P}$ of 2% would then, on average, receive EUR 29.4 for every MWh he sells. The delta of EUR 0.6 per MWh makes a significant difference in the profitability and the valuation of an investment opportunity.

Second, the average of $\Delta\overline{P}$ monotonically increases according to capacity levels. With every marginal increase in size, the absolute value of $\Delta\overline{P}$ decreases, implying that larger turbines come closer to receiving the average price of electricity. In other words, larger turbines receive a higher average price of electricity, so that their produced megawatt-hours are 'worth more' over time, even though they are perfect substitutes to those produced by smaller turbines.

The implication of this result is that, under the assumptions of the same occurred costs for each MWh and the same total production units over time, investors are better off holding (very) large turbines. They are compensated with a higher share of the average electricity price for every unit of production, because the production profile better exploits the dynamics of electricity prices.

To identify how much better they are off in particular, assume the following. Investors earn total of cash flows over time of

$$\text{Cash flows} = n \times (1 + \Delta\overline{P}) \times \overline{P} \times \overline{MWh}, \tag{7}$$

where $\Delta\overline{P}$ is the fraction of the average electricity price that the investor gets less holding the asset and selling electricity. As all scenarios in Figure 4 suggest that $\Delta\overline{P}$ is negative, this implies $(1 + \Delta\overline{P}) < 1$. The variable n is the total months of production, whereas $\overline{P}$ and $\overline{MWh}$ depict the average electricity price and average production.

Let us compare two investors, one holding a share in a small turbine (S) and one in a large turbine (L), however, both holding the equivalent capacity and producing the same total production units.[22] We know the large turbine investor is better off by a share of α. In particular, he is better of by

$$(1+\alpha) \times \underbrace{n \times (1 + \Delta\overline{P_L}) \times \overline{P} \times \overline{MWh}}_{\text{Investor in } L\text{arge turbine}} = \underbrace{n \times (1 + \Delta\overline{P_S}) \times \overline{P} \times \overline{MWh}}_{\text{Investor in } S\text{mall turbine}}, \tag{8}$$

which simplifies to

$$\alpha \equiv \frac{\Delta\overline{P_S} - \Delta\overline{P_L}}{1 + \Delta\overline{P_L}}, \tag{9}$$

where $\Delta\overline{P_L}$ ($\Delta\overline{P_S}$) is the deviation from the average electricity price when investing in a *large*

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[22] For example, one investor owns a 1MW turbine, whereas another investor owns 1/3 of a 3MW turbine. They both then own 1MW in capacity, but in different types of turbines, one being small and one being large. Even though we know from previous calculations that large turbines, on average, produce more than small turbines, this calculation only considers the increase in revenue through receiving different average electricity prices, and therefore assumes the same average production units for the two investments.

(*small*) turbine and α depicts the out-performance of the large turbine over the small turbine. For small numbers, as found in the empirical analysis, α is approximately equal to $\alpha \approx \Delta\overline{P_S} - \Delta\overline{P_L}$. The empirical findings from above suggest that $\alpha > 0$ for every marginal increase in capacity level with one exception in the DK2 price area.

Low- and high-production times

To examine where the differences in $\Delta\overline{P_S}$ and $\Delta\overline{P_L}$ stem from, I repeat this exercise in low- and high-production times and according to Equation (4), which only considers price levels. Specifically, high (low) production times depict periods in which I observe production levels that are in the top (bottom) quintile over the lifetime of the turbine. Figure 5 shows the findings.

The findings of Figure 5 overall confirm the results from the previous analysis and provide more clarity on where differences from average electricity prices originate. In other words, $\Delta\overline{P}$ in high and low production times both contribute to the previously observed results of Figure 4.

With the exception of 1-2MW capacity levels in the DK2 price area, the deviation from average prices is particularly large in high production times, see Figure 5a and 5b. This holds true especially for low-capacity turbines and $\Delta\overline{P}$ gets closer to zero with increases in capacity levels. This trend is not as clear in the DK2 price area, which could originate in the scarce availability of data as shown in Table 3. The total number of turbines in $\{1-2, 2-3, 3+\}$MW capacity levels is significantly lower in the DK2 price area in comparison to DK1.[23] Overall, the numbers are surprisingly large, especially considering that this analysis is based on monthly data only, meaning that the time variation within months is neglected. In high production times, turbines of small capacity levels show to have access to electricity prices that are up to 7% lower than the average over time.

The opposite is true in low production times, see Figure 5c and 5d. When wind turbines produce low levels of output, average electricity prices tend to be higher. This is especially true with regards to small capacity turbines in the DK1 price area. Also, $\Delta\overline{P}$ tends to decrease with capacity levels in the DK1 price area. Similar to high production times, the trend is less pronounced in the DK2 price area. As mentioned, this could be due to the fact that there are much less turbines in the DK2 price area and hence, results are driven by only a few.

I repeat the analysis with different definitions of high and low production times. Specifically, I vary the high and low production times with respect to how much of the top (bottom) distribution I incorporate from 10% to 30%. Results stay robust, but differ in magnitude. They tend to be stronger when incorporating only a very small share of the distribution (10%) and weaken when

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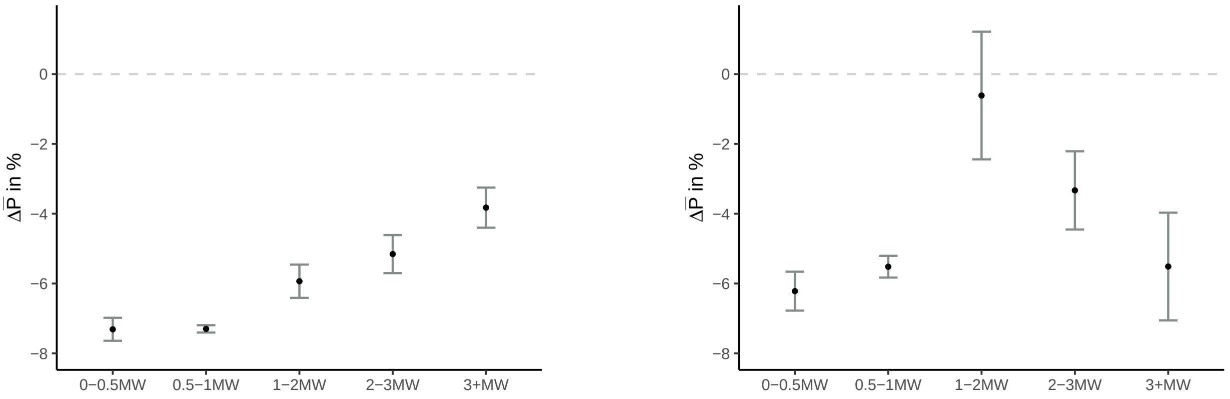
[23] For example, in the 1-2MW capacity level, DK1 has a total number of 255 turbines, whereas DK2 only has 32 turbines. This means that each individual turbine recieves a much higher weight in the presented results for DK2, potentially not confirming the overall trend.

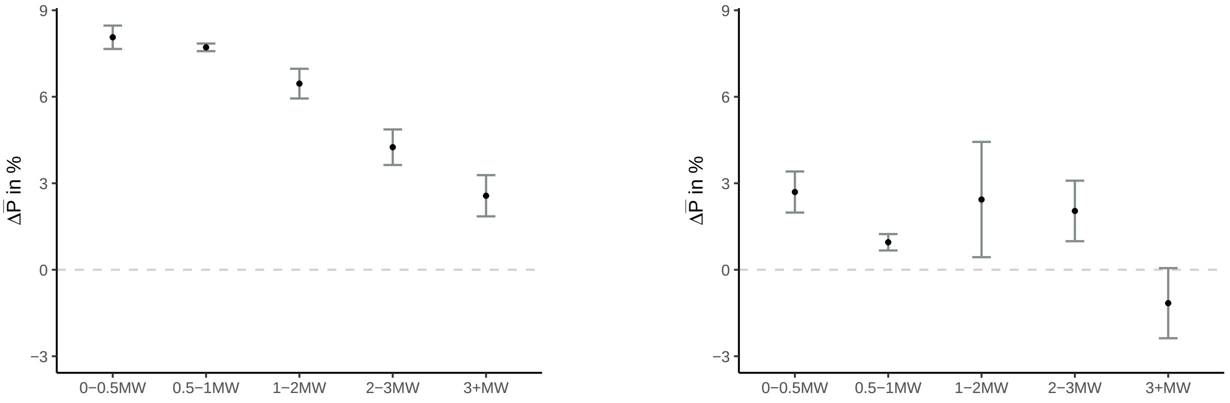
Figure 5: High and low production times

This figure shows price deviations from average prices for chosen capacity levels in high and low production times. In particular, I consider the top and bottom 20% of production periods and look at average prices in comparison to average prices throughout the entire time horizon of each turbine according to Equation (4). Black points in the graph depict averages and the error bars are 95%-confidence intervals.



(a) High production in DK1 **(b)** High production in DK2

(c) Low production in DK1 **(d)** Low production in DK2



widening the definition of high and low production times (getting closer to 30%).

These findings provide evidence on where the price differential of $\Delta\overline{P}$ across capacity levels and as found in Figure 4 root in. In a nutshell, Danish wind energy production seems to be countercyclical to electricity prices (negative correlation). This is particularly true for small turbines and the effect weakens with increases in capacity levels. This is important to investors as the implication is that they receive higher average electricity prices when investing in large turbines.

4.3 Regression analysis

The previous results offer evidence on negative correlations between electricity prices and wind energy production and show how they impact an investment's profitability. This chapter builds on these findings and extends them in a regression framework, where I additionally control for other factors as total electricity consumption, lagged prices and seasonality through month fixed effects.

In particular, I examine the relationship between wind energy production and electricity prices according to Equation (6). As before, I subdivide the sample of wind turbines in different capacity levels and determine how they are exposed to or impact electricity prices.

Regression (6) adjusts for electricity consumption in the economy, which is the sum of provided electricity from other sources than wind energy in the Danish economy. Furthermore, it adjusts for lagged electricity prices and month fixed effects to account for seasonality patterns in the electricity price movements throughout the year. Table 5 shows the results.

Table 5: Price vs. production

The table exhibits the panel regression results according to Equation (6). Specifically, I subset the data sample with regards to capacity levels. The dependent variable is the relevant area log(price) in DK1 or DK2 of the individual turbine. Production estimates are standardized through Equation (1) and expressed in GWh. I adjust for lagged log(prices) with γ as well as total electricity consumption through κ with the explanatory variable measured in TWh. Furthermore, I account for seasonality in prices, production outputs and consumption through monthly time fixed effects ($M_{j,t}$). I cluster standard errors by time (month) and document them in the brackets below the estimates.

	Dependent variable:					
	p_t					
	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
	(1)	(2)	(3)	(4)	(5)	(6)
β: Turbine prod. in GWh	-0.444^{***}	-0.361^{***}	-0.630^{***}	-0.338^{***}	-0.266^{**}	-0.291^{**}
	(0.098)	(0.080)	(0.150)	(0.070)	(0.111)	(0.123)
γ: Lagged el. price p_{t-1}	0.775^{***}	0.766^{***}	0.784^{***}	0.781^{***}	0.741^{***}	0.733^{***}
	(0.056)	(0.056)	(0.055)	(0.059)	(0.068)	(0.083)
κ: El. consumption in TWh	0.044^{***}	0.047^{***}	0.042^{***}	0.044^{***}	0.069^{***}	0.090^{***}
	(0.008)	(0.008)	(0.007)	(0.008)	(0.010)	(0.017)
Constant α	-0.015	-0.085	0.040	-0.047	-0.370^{*}	-0.714^{**}
	(0.216)	(0.214)	(0.215)	(0.220)	(0.195)	(0.346)
Month fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Observations	585,064	145,896	375,707	36,367	17,763	9,331

Note: *p<0.1; **p<0.05; ***p<0.01

Turbine production units are in GWh instead of MWh to make the coefficient estimate easier to read and interpret. The time horizon goes from January 2005 until the end 2017, except for the final bracket of 3+MW, where data is available from January 2010.[24]

The interpretations of production coefficients in Table 5 is as follows. For every unit increase as measured in GWh, the electricity price moves relatively according to the coefficient. For example, when looking at the first column $Total$, the electricity price decreases 44.4% for every one-GWh increase in turbine production (β).

The results from Table 5 show that smaller turbines of $\{0-0.5, 0.5-1, 1-2\}$MW are strongly negatively correlated to electricity prices. For every additional GWh of production, they are faced with a decrease in electricity prices of between 36.1% to 63.0%.

This effect is weaker for larger turbines in the $\{2-3, 3+\}$MW brackets, where coefficients are around -26.6% to -29.1%. This means that for every marginal GWh increase in production, prices decrease relatively less in comparison to smaller turbines. Furthermore, significance decreases.

These results confirm the findings from the previous analysis and suggest that smaller turbines tend to receive lower prices for their electricity output. Larger turbines, on the other hand, are less negatively correlated to electricity prices. As previously mentioned, these results have important implications for investors. All else equal, high-capacity turbines receive higher average prices per MWh, making them more profitable than their smaller peers.

4.4 Robustness checks and other tests

As robustness checks, I run two alternative regression specifications, see Appendix C. First, I address stationary concerns by computing deltas for the dependent and explanatory variables and re-run regressions. Table C.1 shows the results. Second, I also run the regression specification for real prices. Table C.2 documents the findings. Results are robust to these alternating approaches and trends remain similar or become even stronger as in the main specification.

Moreover, I run regressions on an individual turbine level (also in Appendix C). The findings confirm the results. However, they also signal that the distribution of coefficients is not normal and sometimes wide-spread, suggesting that production outputs and the correlation to electricity prices can vary substantially across turbines. This suggests that α from Equation (9) may significantly vary on a turbine-individual level.

Finally, I run the regression specification of Equation (6) on a 24-month rolling window to examine time-varying correlations. Figure C.2 in Appendix C shows the results. Correlations vary over time and seem pronounced during the financial crisis. However, excluding the financial crisis

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[24] Conducting all regressions from January 2010 instead does not significantly impact the results.

does not significantly impact the results, see Table C.3 in Appendix C. Furthermore, a regression incorporating the interaction between the crisis and production does not confirm that correlations, on average, are particularly pronounced in economically distressed times.

5 An Excursion into High-Frequency Data

The empirical analysis is based on production-level data of a large sample of wind turbines in Denmark. Specifically, the data exhibits monthly production outputs, which, combined with the relevant electricity price (from the DK1 or DK2 price area), leads to the findings of the previous sections.

One concern is that much of the variation in the production and electricity price dynamics is lost in monthly data points. This section is to address this concern through the investigation of a unique data set obtained from a mid-sized Danish infrastructure fund. Specifically, the data contains high-frequency production and wind speed data in 10-minute intervals from on 81 turbines. Except for 4 turbines, they locate in the DK1 price area (western Denmark). Production data is available from 31/05/2017 00:00 until 11/12/2019 22:00. Capacity levels range from 0.5MW to 1.5MW.[25] Additionally, the data set contains wind speed data for each turbine. As previously, I adjust the production output data according to Equation (1), so that I obtain production outputs per MW of capacity.

As in the main analysis, I complement the data with hourly spot prices from the DK1 and DK2 price areas and electricity consumption information for the Danish market from Nord Pool AS. I aggregate the 10-min-frequency production data to hourly estimates and merge them with spot prices and consumption level statistics from the relevant area into a panel data set. In a nutshell, I obtain the same data set as for the previous empirical analysis only on a high-frequency basis and for a subset of turbines and time.

For the analysis, I split the data in two subsamples, one of which I call *small* and one of which I refer to as *large* turbines. The threshold is at 0.75MW, which approximately leaves me with the same number of turbines in each of the brackets (40 small and 41 large turbines).

5.1 Price deviations in high-frequency environments

I repeat the analysis according to Equation (3) in a high-frequency (hourly data) environment and thereby address the concern of neglecting relevant short-term production and price dynamics. The analysis does not distinguish between the two areas of DK1 and DK2, because all except for four turbines operate in the same area. The analysis considers the entire time horizon and also takes

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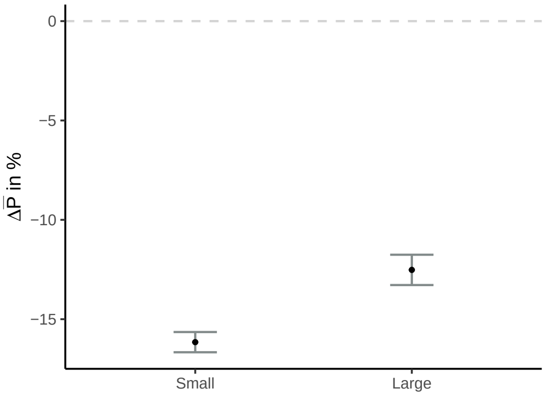
[25] The data is available upon request and in agreement with the fund management firm.

a closer look at high versus low production times. Figure 6a shows the results on the total price deviations.

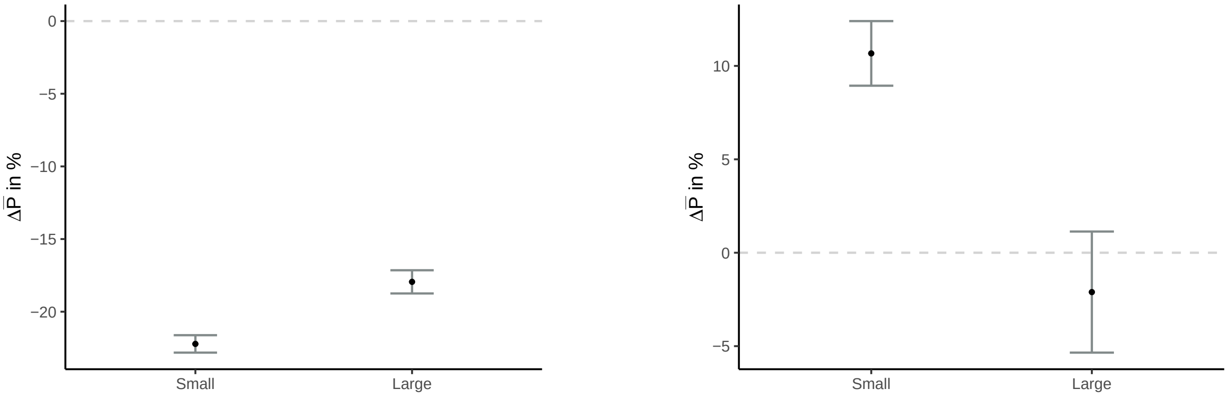
Figure 6: Price deviations in high-frequency environments

Figure 6a shows price deviations from average electricity prices for small and large turbines and as calculated by Equation (3). Furthermore, I split the data sample according high and low production times. In particular, high and low production times are defined as the the top and bottom 20% of production periods over the available time horizon. I calculate the price deviation in these times according to Equation (4). Figure 6b and 6c show the result. The underlying data for all plots are high frequency production level data from a private investor containing a total of 81 turbines. The data depicts 10-minute production level data, which is aggregated to hourly estimates and then matched with the relevant electricity spot price (DK1 or DK2). Error bars are the 95%-confidence intervals.

(a) Average price deviation



(b) High production periods **(c)** Low production periods



The previous finding, implying that larger turbines sell electricity outputs at a higher price, persists. However, the magnitudes of results are much higher in comparison to what the monthly data suggests. Here, the average price differential $\Delta\overline{P}$ from the average electricity price is -16.2%

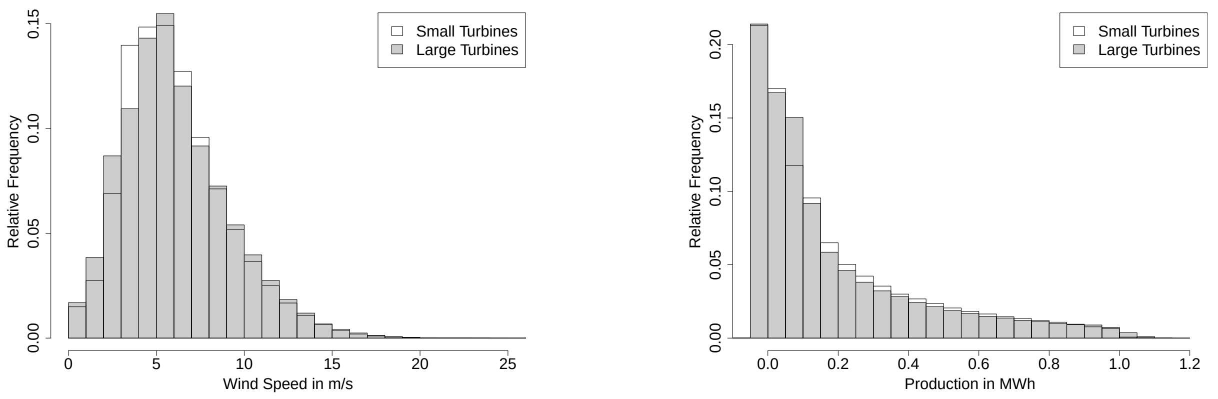
for small and -12.5% for large turbines, which is much higher than the results in Figure 4. Also, a difference-in-difference estimation shows that the two estimates are significantly different from one another.

Second, Figure 6b and 6c consider high and low production times only and according to Equation (4). Although, relative numbers are much higher when compared to monthly data, the main result remains unchanged. Larger turbines 'outperform' smaller turbines in high-production times at a significant level, or put differently, are exposed to relatively higher prices. Small (large) turbines yield an electricity price, which is 22.2% (17.9%) lower than the average price. I repeat the analysis for low production times, which are effectively hours during which turbines do not produce any electricity. When small turbines do not produce, prices tend to be 10.7% higher than the average for small turbines. Surprisingly, prices are 2.1% lower than average under low production times of large turbines. In these times, both types of turbines do not yield revenue, which is particular harmful for small turbines, because prices tend to be much higher than average. The implication of these results is that it is different times during which small and large turbines produce high and low outputs, respectively.

To further examine these results, I plot the relative distribution of wind speeds and production outputs, see Figure 7a and 7b.[26]

Figure 7: High-frequency turbine output and wind speed distributions

These plots show the relative distributions of wind speeds and production outputs across a sample of small and large turbines. Specifically, the sample documents 10-minute wind speed and production output data, which is aggregated to hourly estimates. The data was provided by a private renewable energy investor and contains observations from a total of 81 turbines. Small turbines are those with a capacity of less than 0.75MW, and vice versa.



(a) Wind speeds

(b) Production outputs

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[26] Figure D.1 in Appendix D additionally shows a scatter plot over wind speeds and production outputs.

Overall, I find only minor differences in the samples' distributions. There are slight deviations in the lower levels of wind speeds and production outputs. This makes the distribution of wind speed exposure wider for large turbines. Also, large turbines seem to produce low levels of power more often than small turbines. The results suggest that these power outputs come at a time of relatively high prices, putting larger turbines in a position of exploiting a higher average price. That said, it must hold true that the distribution of production outputs by large turbines allocates at an overall more favorable place in the time series of electricity prices.

5.2 A high-frequency regression framework

I apply a similar regression analysis as under the monthly data sample, see Equation (6). Specifically, I run

$$P_{i,t} = \alpha + \beta MWh_{i,t} + \gamma P_{i,t-1} + \kappa GWh_t + \sum_{j=1}^{11} \mu_j M_{j,t} + \sum_{k=1}^{6} \omega_k W_{k,t} + \sum_{l=1}^{23} \mu_l H_{l,t} + \epsilon_{i,t}, \tag{10}$$

where $P_{i,t}$ is the relevant price of electricity (in Euro) for each turbine, depending on whether it locates in price area DK1 or DK2, with $P_{i,t-1}$ being the lagged value. This regression is run on real instead of log-prices as there are also time periods that document negative price levels. $MWh_{i,t}$ is the production output in megawatt-hours of turbine i and GWh_t is the aggregated consumption of electricity in gigawatt-hours in Denmark, both at time t.[27] I adjust for month fixed effects, weekday fixed effects as well as hourly fixed effects through $M_{j,t}$, $W_{k,t}$ and $H_{l,t}$, respectively. Additionally to this specification, I also run the regression on deltas. Table 6 shows the results.

The results are consistent with previous findings. The production by smaller turbines documents more negative correlations to electricity prices than large turbines. Even though the sample only incorporates capacity levels from 0.5MW to 1.5MW, the trend from small to large turbines seems very consistent. For example, every additional MWh produced by a small turbine (Column 2) comes along with a negative price change of Euro 2.66, whereas a large turbine only experiences a negative price change of Euro 1.70 (Column 3). The results are further robust to the alternative application, where dependent and independent variables depict changes in values from the previous period (Δ), however, the difference becomes smaller, see Columns 5 and 6.

Overall, the application of the empirical framework to high-frequency data confirms the previous results. Larger turbines tend to be compensated with a higher average price of electricity than

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[27] Instead of working with GWh and TWh as in the previous analysis, I switch to MWh and GWh, respectively, to adjust coefficients in their magnitude. High frequency data does not require upscaling at the same rate as before.

Table 6: Electricity production vs. prices in high-frequency environments

The table exhibits the regression results according to Equation (10). Also, I run the regression on changes to the previous period (Δ) in dependent and independent variables. Specifically, I subset the data sample with regards to capacity levels. The dependent variable is the relevant hourly electricity price in area DK1 or DK2 of the individual turbine. Production estimates, also hourly, are standardized through Equation (1) and expressed in MWh. I control for lagged electricity prices (γ) as well as electricity consumption (κ) with the explanatory variable measured in GWh. Furthermore, I account for seasonality in price, production outputs and consumption estimates through monthly time fixed effects, weekday fixed effects as well as hourly fixed effects. Standard errors are clustered by time and documented in the brackets below the estimates.

	Dependent variable:					
	P_t			ΔP_t		
	Total	Small	Large	Total	Small	Large
	(1)	(2)	(3)	(4)	(5)	(6)
β: Turbine production MWh	-2.094^{***}	-2.658^{***}	-1.698^{***}			
	(0.246)	(0.265)	(0.240)			
γ: El. price P_{t-1}	0.934^{***}	0.927^{***}	0.939^{***}			
	(0.009)	(0.009)	(0.009)			
κ: El. consumption GWh	1.106	1.194	1.048			
	(0.940)	(0.947)	(0.934)			
β: Turbine production ΔMWh				-2.198^{***}	-2.281^{***}	-2.129^{***}
				(0.285)	(0.334)	(0.273)
γ: El. price ΔP_{t-1}				0.125^{***}	0.130^{***}	0.120^{***}
				(0.040)	(0.039)	(0.040)
κ: El. consumption ΔGWh				12.658^{***}	12.560^{***}	12.743^{***}
				(2.201)	(2.206)	(2.199)
Constant α	-1.483	-1.237	-1.645	-0.333	-0.330	-0.337
	(1.829)	(1.838)	(1.822)	(0.271)	(0.270)	(0.271)
Month fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Weekday fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Hour fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,593,184	734,622	858,562	1,578,103	727,331	850,772

Note: *p<0.1; **p<0.05; ***p<0.01

small turbines. Also, the marginal additional production output tends to be compensated with less of a discount in the price of electricity for larger turbines. Magnitudes however, are significantly higher than the monthly data suggests, implying that the short-term dynamics of production and electricity prices largely matter.

6 Discussion: Is the bigger really the better?

This paper presents evidence that large turbines yield higher average prices of electricity in comparison to their smaller peers. The empirical analysis suggests that this finding roots in the fact that the production by large turbines is less negatively correlated to electricity prices. All else equal, an investor would therefore be better off owning a share in a large turbine.

This key finding of *the bigger the better* makes an important assumption however, which is that all other variables are equal. These other variables specifically refer to the cost side of such investments. In particular, investors are exposed to two main sources of costs. First, operational expenditures (OPEX), which occur throughout the lifetime of a project, and second, capital expenditures (CAPEX), which are due during the investment (or development) into a project depict the most relevant cost drivers.

To compare investment opportunities in energy assets and take into account both expected production as well as costs over time, decision-making typically relies on the concept of the levelized cost of energy (LCOE). Specifically, the LCOE depicts the ratio of total costs over time divided by the total energy output (Lai and McCulloch, 2017).[28] Comparing this ratio among a subset of projects helps investors gain a quick overview of which ones seem most profitable. It is relevant to point out that the concept of LCOE does not inherently incorporate uncertainty drivers, however, it has proven to serve as a useful indicator in the industry to compare investment opportunities not only within but also across markets.

If and only if this ratio is the same across turbines, an investor is as a matter of fact better off owning a share in a larger one. If instead this ratio significantly differs across turbines, this can either strengthen or reverse profitability differences. For example, a small turbine that is more negatively correlated to energy prices than a large turbine and hence, $\Delta\overline{P_S} < \Delta\overline{P_L}$, might still be the better investment opportunity if $LCOE_S < LCOE_L$ to an extent where it offsets the difference between $\Delta\overline{P_S}$ and $\Delta\overline{P_L}$.

This paper does not offer any empirical background on distributions and levels of LCEOs across wind energy investment opportunities. Indeed, this could serve as another research venue and would help obtain a more complete picture on this asset class. The statement of *the bigger the better* therefor only holds true under the assumption of equal costs across turbines of different capacity levels and should be interpreted as such.

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[28] LCOE derives from he ratio of costs over output over time. Specifically, it is:

$$LCEO = \frac{present\ value\ of\ costs\ over\ project\ lifetime}{present\ value\ of\ energy\ production\ over\ project\ lifetime} \tag{11}$$

The variable of costs take into consideration capital and operational expenditures. In the case of conventional energy investments, it further considers the cost of commodities that are required for production. The denominator only considers energy outpout over time. The present value of the ratio helps as an indication to compare investment opportunities.

7 Conclusion

This paper empirically examines wind energy production uncertainty and correlations to electricity prices. Next to comparing turbines with regards to absolute and relative production volatility, it investigates the relationship between production and electricity prices across capacity levels and sheds light on its monetary implications.

I find that production outputs by large-capacity turbines is higher while (relative) volatility is lower in comparison to smaller peers. I further document that large-capacity turbines are less negatively correlated to electricity prices, suggesting that they sell electricity outputs at higher prices on average. These findings have important implications. They suggest lower volatility in cash flows over time and higher risk-adjusted returns by large-capacity turbines. Additionally, these features could result in more favorable financing conditions.

Furthermore, results persist in a sample of high-frequency data, however, the magnitudes of estimates are significantly higher than monthly data suggests. This indicates that short-term dynamics largely matter for the valuation of investment opportunities.

These findings are important for investors to consider when allocating capital to the asset class of wind energy. All else equal, investors are better off following the dogma of *the bigger the better!*

Appendices

A Turbine Data

In this appendix section, I show more information on the turbine data used in the analysis.

Figure A.1: Wind turbine distribution by capacity

This figure shows the number of turbines in the data sample by the Danish Energy Agency and according to capacity levels as indicated by MW. Not all turbines shown in this plot are still in production today.

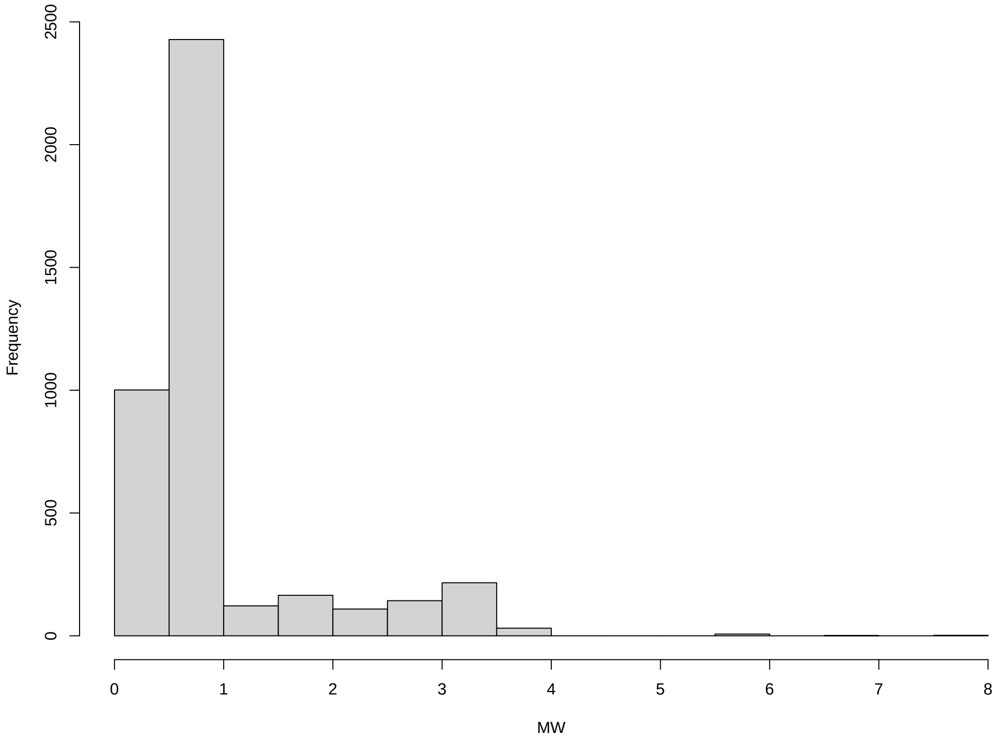
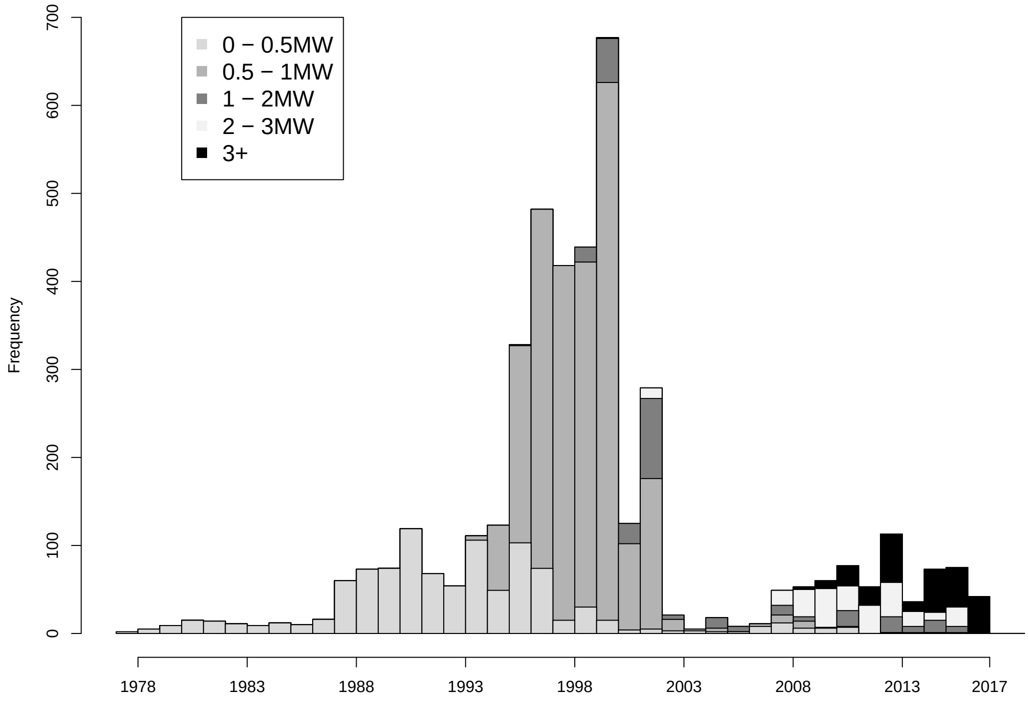


Figure A.2: Turbine investments by vintage

The figure shows the number of added turbines according to capacity levels over time. Note that even though vintages date back to 1978, production data is only available from 2002. Not all turbines shown in this plot are still in production today. In fact, old turbines in this sample might have been replaced (re-powered) with newer and perhaps more powerful ones.



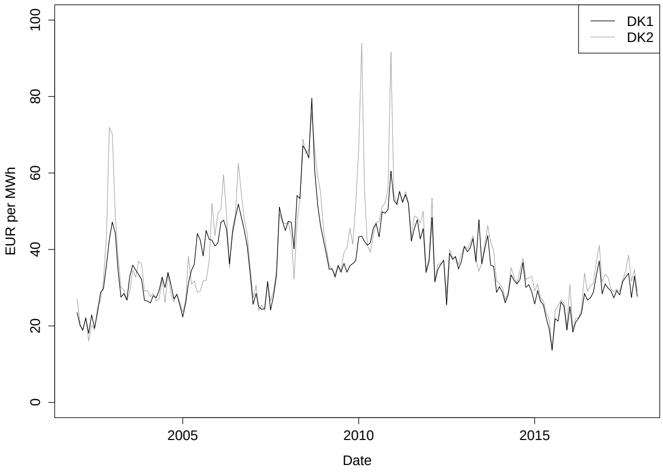
B Electricity Prices and Production

In this appendix section I show more information on electricity prices and their relationship to wind energy production.

Figure B.1: Electricity prices over time

Figure B.1a represents monthly averages of the electricity spot prices in the price areas of DK1 and DK2 as obtained by Nord Pool AS. Prices are denoted in EUR per MWh. The data goes from January 2002 until December 2017. The DK1 price area covers Jutland and Fyn (the western area), whereas the DK2 price area consists of Zealand and the Capital Region (the eastern area). Figure B.1b exhibits the differences in the electricity spot prices as denoted by the two price areas of DK1 and DK2.

(a) Electricity prices over time



(b) Differences in DK1 and DK2 price areas

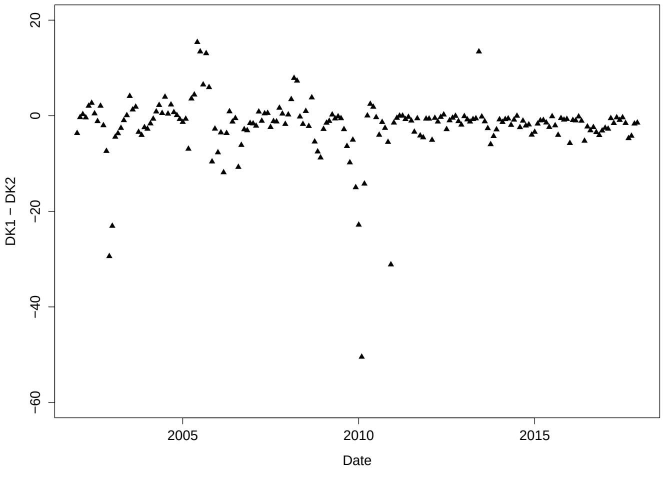


Figure B.2: Production vs. price

This figure plots the average production of all the turbines in the sample over time as well as the SYS spot price of electricity. Production outputs for all turbines are adjusted according to Equation (1). The system (SYS) electricity spot price is the balanced price on the Nordic electricity market between the Nordic areas and is denoted in EUR per MWh.

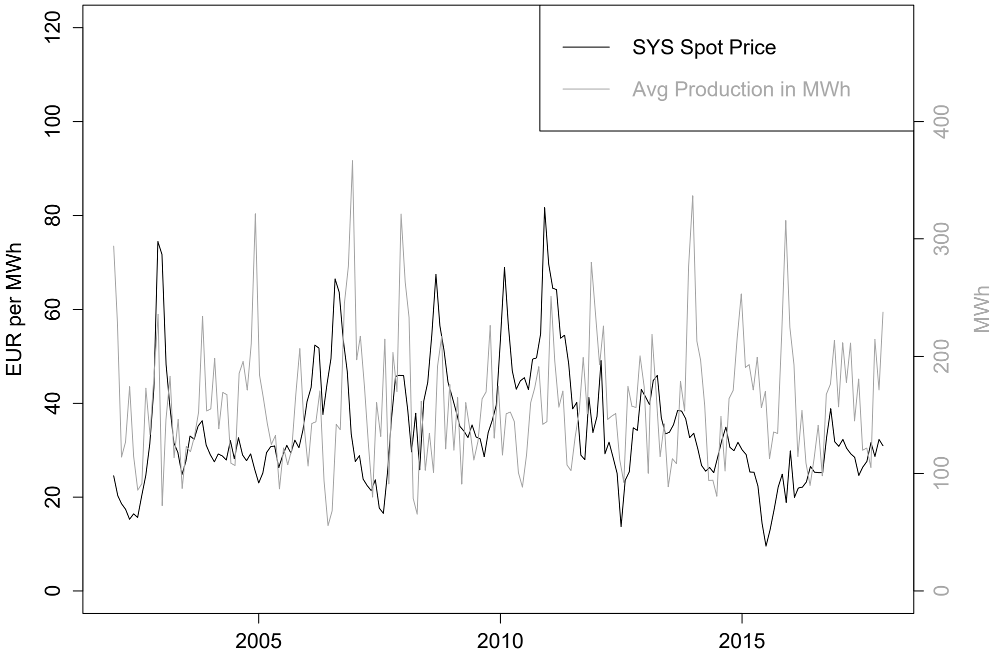


Table B.1: Differences in production vs. prices

This table reports the results from Figure 4. $\Delta\overline{P}$ in % depicts the average price deviation of turbines according to capacity levels and based on Equation (3). The difference (diff) is the delta between two adjacent capacity levels' price difference. The t-test documents whether this delta is significantly different from zero.

	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
$\Delta\overline{P}$ in %	-1.824	-2.202	-1.929	-1.573	-1.120	-0.626
diff			0.273	0.356	0.453	0.494
t-test			-3.197	-7.729	-7.934	-8.131
Panel B: DK2						
$\Delta\overline{P}$ in %	-1.179	-1.476	-1.086	-0.711	-0.858	-0.587
diff			0.389	0.376	-0.148	0.271
t-test			-2.609	-1.210	0.466	-2.383

C Robustness Regressions and other Tests

C.1 Additional regressions

In this appendix section I show additional regression results based on variations of Equation (6).

Table C.1: Delta regressions of production vs. electricity prices

The table shows the regression results of $\Delta P_{i,t} = \alpha + \beta \Delta GWh_{i,t} + \gamma \Delta P_{i,t-1} + \kappa \Delta TWh_t + \sum_{j=1}^{11} \mu_j M_{j,t} + \epsilon_{i,t}$. Specifically, I subset the data sample with regards to capacity levels. The dependent variable is the relevant area price change in DK1 or DK2 of the individual turbine. Production estimates of turbine i and at time t are standardized through Equation (1) and documented in GWh. I control for lagged changes in electricity prices (γ) as well as changes in electricity consumption through κ with the explanatory variable measured in TWh. Furthermore, I account for seasonality in price, production outputs and consumption estimates through monthly time fixed effects. Standard errors are clustered by time and documented in the brackets below the estimates.

	Dependent variable:					
	ΔP_t					
	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
	(1)	(2)	(3)	(4)	(5)	(6)
β: Turbine production ΔGWh	-10.568	-9.588	-11.709	-9.876	-4.141	-3.700
	(7.257)	(6.667)	(8.294)	(6.275)	(3.644)	(4.820)
γ: El. price ΔP_{t-1}	-0.111	-0.106	-0.105	-0.124	-0.228^{**}	-0.285^{***}
	(0.092)	(0.099)	(0.092)	(0.089)	(0.089)	(0.103)
κ: El. Consumption ΔTWh	2.640^{***}	2.880^{***}	2.578^{***}	2.422^{***}	2.610^{***}	2.085^{***}
	(0.415)	(0.411)	(0.424)	(0.404)	(0.534)	(0.548)
Constant α	-1.990^{***}	-2.405^{***}	-1.815^{***}	-1.773^{***}	-2.373^{***}	-2.406^{***}
	(0.456)	(0.463)	(0.469)	(0.400)	(0.549)	(0.684)
Time fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Observations	580,848	144,895	373,279	36,081	17,511	9,082
Note:						*p<0.1; **p<0.05; ***p<0.01

Table C.2: Real price regressions of production vs. electricity prices

The table shows the regression results of $P_{i,t} = \alpha + \beta GWh_{i,t} + \gamma P_{i,t-1} + \kappa TWh_t + \sum_{j=1}^{11} \mu_j M_{j,t} + \epsilon_{i,t}$. Specifically, I subset the data sample with regards to capacity levels. The dependent variable is the relevant nominal electricity price of area DK1 or DK2 of the individual turbine. Production estimates of turbine i at time t are standardized through Equation (1) and documented in GWh. I control for lagged electricity prices (γ) as well as electricity consumption (κ) with the explanatory variable measured in TWh. Furthermore, I account for seasonality in price, production outputs and consumption estimates through monthly time fixed effects. Standard errors are clustered by time and documented in the brackets below the estimates.

	Dependent variable:					
	P_t					
	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
	(1)	(2)	(3)	(4)	(5)	(6)
β: Turbine Production GWh	-13.464^{***}	-11.171^{***}	-19.379^{***}	-9.995^{***}	-4.658	-5.260
	(3.412)	(2.875)	(5.476)	(2.120)	(3.056)	(3.690)
γ: El. Price P_{t-1}	0.761^{***}	0.744^{***}	0.772^{***}	0.776^{***}	0.723^{***}	0.728^{***}
	(0.068)	(0.072)	(0.067)	(0.068)	(0.064)	(0.075)
κ: El. Consumption TWh	1.702^{***}	1.885^{***}	1.613^{***}	1.624^{***}	2.584^{***}	2.851^{***}
	(0.322)	(0.340)	(0.309)	(0.332)	(0.424)	(0.580)
Constant α	-24.056^{***}	-28.230^{***}	-21.221^{***}	-23.405^{***}	-40.559^{***}	-44.886^{***}
	(5.958)	(6.167)	(5.813)	(6.122)	(7.701)	(10.669)
Time fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Observations	585,064	145,896	375,707	36,367	17,763	9,331

Note: *p<0.1; **p<0.05; ***p<0.01

C.2 Individual turbine exposure

In this appendix section I repeat the regression analysis according to Equation (6) on an individual turbine level. Specifically, I run regressions of every single turbine's production on the relevant electricity price (DK1 or DK2), while adjusting for consumption, lagged prices, and month fixed effects. I only run the individual turbine regression if there are at least 10 observations for the individual unit.

I store all β-coefficients on production and plot the distributions according to capacity levels. The results aim to provide an understanding on cross-sectional distribution in correlations to electricity prices. Figure C.1 shows the results.

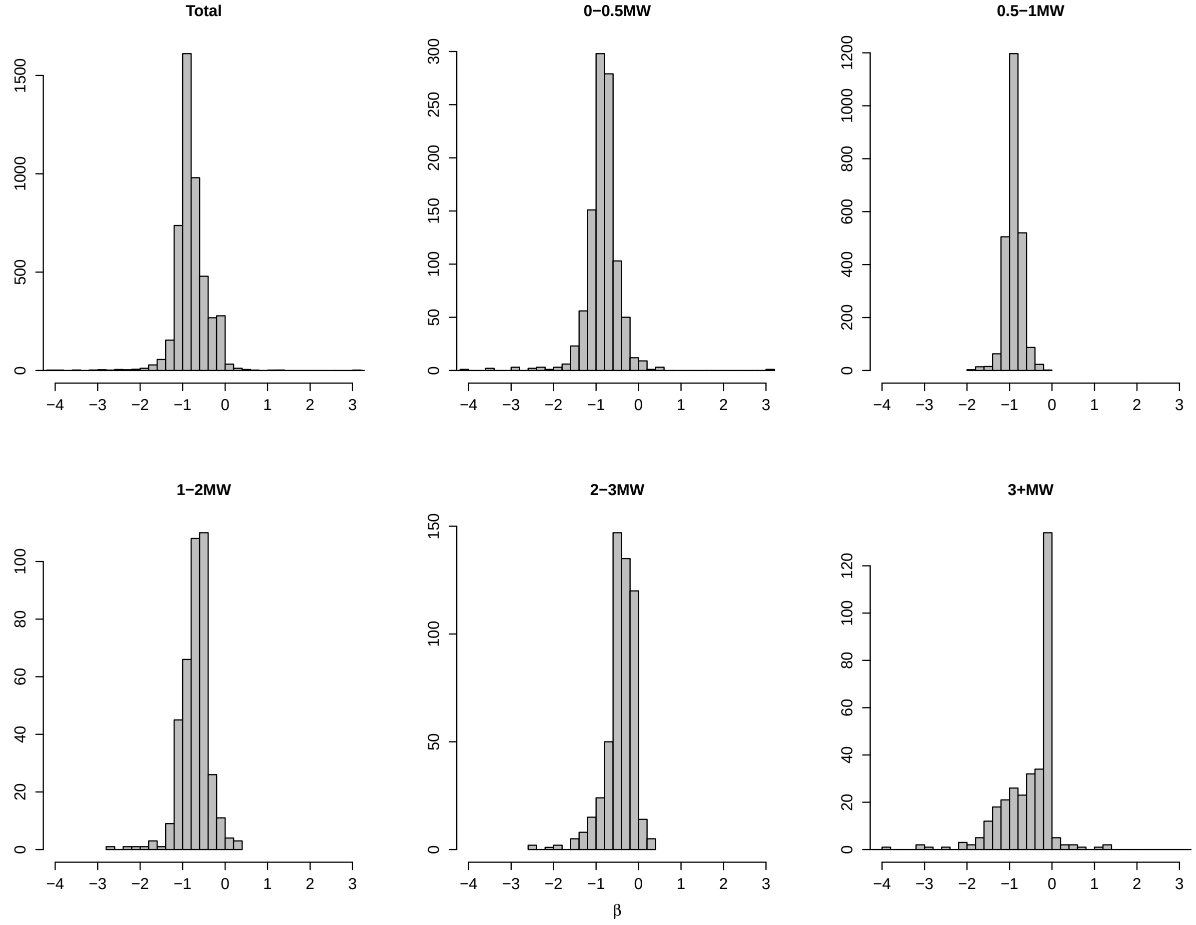
Figure C.1 shows that the distribution mass of smaller turbines' β-coefficients tends to be more negative in comparison to that of large-scale turbines, which confirms previous results. A t-test on the distributions of each capacity level's β-coefficients shows that all are significantly different from zero, however, large turbines deviate less from zero than their smaller peers when comparing means.

The distribution of 3+MW turbines' β-coefficients is unique in comparison to others. The reason is that in this sample of turbines there is a number of wind parks. When listing wind parks, the sample distinguishes between individual turbines in the park, but lists the same production numbers for every turbine. This implies that single parks have an impact on the results within given categories as they represent higher weights than single turbines. Furthermore, there is also a small number of observations that are far from zero, suggesting that an individual turbine's correlation to electricity prices can vary significantly and therefor resulting in much higher or lower returns.

In a nutshell, Figure C.1 confirms the results from Table 5. Smaller and individual turbines' electricity production, on average, is more negatively correlated to electricity prices than their larger competitors. Furthermore, results under 3+MW capacity are partly driven by a number of wind parks as turbines in a given park exhibit the same production level data.

Figure C.1: Electricity vs. production

The histograms plot the distributions of β_i-coefficients obtained from the turbine-individual (i) regressions of $p_{i,t} = \alpha + \beta_i GWh_{i,t} + \gamma p_{i,t-1} + \kappa TWh_{i,t} + \sum_{j=1}^{11} \mu_j M_{i,t} + \epsilon_{i,t}$, grouped by capacity levels. The dependent variable is the log-price in the respective price area of DK1 or DK2 of the individual turbine. Production estimates of turbine i at time t are standardized through Equation (1) and documented in GWh. I adjust for lagged electricity log-prices and aggregated electricity consumption through γ and κ (measured in TWh). Furthermore, I account for seasonality in price, production outputs, and consumption estimates through monthly time fixed effects.

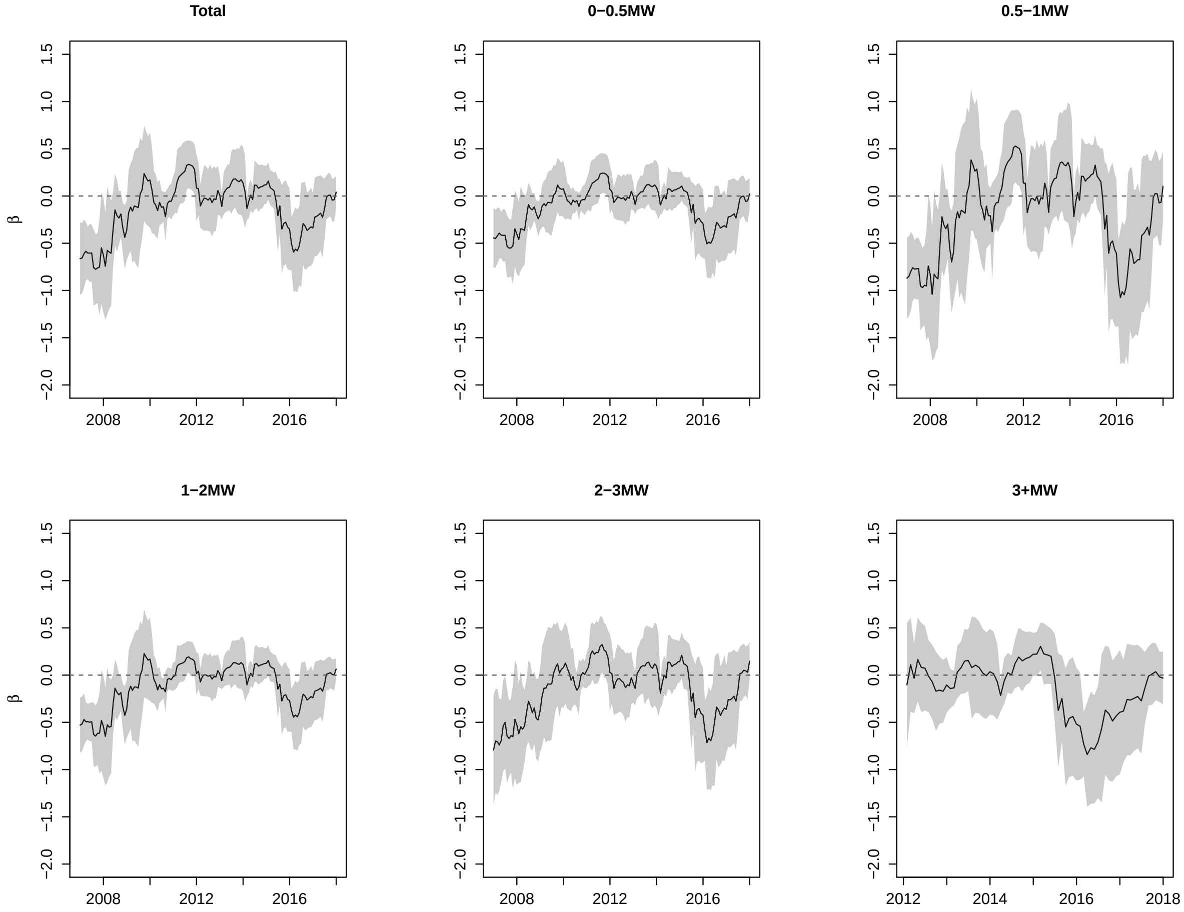


C.3 Exposure over time

To further examine the results of Table 5, I investigate time-varying exposures of wind energy production to electricity prices through rolling regressions. In essence, I redo the analysis from Table 5 and based on Equation (6) but on a rolling basis of 24 months. This allows me to observe exposure throughout time. Figure C.2 shows the results.

Figure C.2: Rolling correlations between output and electricity spot prices

The figure exhibits the rolling beta estimates of the regression results of $p_{i,t} = \alpha + \beta GWh_{i,t} + \gamma p_{i,t-1} + \kappa TWh_t + \sum_{j=1}^{11} \mu_j M_{j,t} + \epsilon_{i,t}$, grouped by the capacity of the turbines. The rolling window is 24 months. Specifically, I subset the data sample with respect to capacity levels. The dependent variable is the relevant area log-price in DK1 or DK2, depending on where the individual turbine locates. Production estimates of turbine i at time t are standardized through Equation (1) and documented in GWh. I adjust for lagged electricity log-prices with γ and aggregated electricity consumption through κ with the explanatory variable measured in TWh. Furthermore, I account for seasonality in price, production outputs and consumption estimates through monthly time fixed effects. Standard errors are clustered by time. Gray intervals around the observations show 95% confidence intervals.



It shows that correlation is volatile throughout time. Negative correlations are more likely than not except for the 3+MW capacity level. Turbine production exposure to electricity prices is particularly volatile in the 0.5-1MW capacity bracket.

The results demonstrate another interesting observation when looking at the time horizon of 2007 until 2009. Almost all capacity level experience strong negative exposures to electricity prices.[29] As this time-horizon is characterized by the financial crisis, this finding might have implications for times of economic distress. It suggests that wind energy production is more negatively exposed to electricity prices during crises, in which case investors need to anticipate even lower earnings due to higher than normal negative correlations. If true, the notion of real assets (as wind energy investments) offering a hedge against crises therefor loses some of its merit. The next appendix section conducts additional analysis on whether times of crises are indeed of economic significance with regards to correlations.

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[29] The 3+MW capacity bracket does not have any data available for the time of the financial crisis, because there were no turbines in operation, see Appendix A, Figure A.2.

C.4 Excluding the financial crisis

The findings of Figure C.2 suggest that regression results from Table 5 might be driven by the time horizon of the financial crisis. To test whether the results from Table 5 hold true when ignoring this time horizon, I exclude the crisis from the data sample. If it was true that results are time-varying and driven by the economic distress during the crisis, then the exclusion of this particular time will lead to different findings.

I repeat the regression of Equation (6) but only consider times outside the financial crisis. In particular, I run the same regression specification as before but exclude the time horizon from December 2007 until June 2009.[30] Table C.3 shows the results.

Table C.3: Price vs. production excluding the financial crisis

The table shows the regression results of $p_{i,t} = \alpha + \beta GWh_{i,t} + \gamma p_{i,t-1} + \kappa TWh_t + \sum_{j=1}^{11} \mu_j M_{j,t} + \epsilon_{i,t}$ as specified in Equation (6). I subset the data sample with respect to capacity levels and run the regression excluding times of the financial crisis from December 2007 until June 2009 as defined by the US Business Cycle Expansions and Contractions by the National Bureau of Economic Research. The dependent variable is the relevant area log-price in DK1 or DK2, depending on where the individual turbine locates. Production estimates of turbine i at time t are standardized through Equation (1) and documented in GWh. I adjust for lagged electricity log-prices through γ and aggregated electricity consumption through κ with the explanatory variable measured in TWh. Furthermore, I account for seasonality in prices, production outputs and consumption estimates through monthly time fixed effects. Standard errors are clustered by time and documented the brackets below the estimates.

	Dependent variable:					
	p_t					
	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
	(1)	(2)	(3)	(4)	(5)	(6)
β: Turbine Prod. GWh_t	-0.507^{***}	-0.426^{***}	-0.737^{***}	-0.374^{***}	-0.275^{**}	-0.291^{**}
	(0.102)	(0.087)	(0.152)	(0.074)	(0.112)	(0.123)
γ: El. Price p_{t-1}	0.754^{***}	0.746^{***}	0.761^{***}	0.763^{***}	0.741^{***}	0.733^{***}
	(0.053)	(0.053)	(0.052)	(0.057)	(0.068)	(0.083)
κ: El. Consumption TWh_t	0.044^{***}	0.047^{***}	0.042^{***}	0.044^{***}	0.072^{***}	0.090^{***}
	(0.008)	(0.008)	(0.007)	(0.008)	(0.010)	(0.017)
Constant α	0.064	-0.003	0.133	0.014	-0.408^{**}	-0.714^{**}
	(0.223)	(0.223)	(0.223)	(0.227)	(0.201)	(0.346)
Month fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Observations	517,340	128,236	329,983	32,390	17,400	9,331

Note: *p<0.1; **p<0.05; ***p<0.01

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[30] This time span is commonly referred to as the horizon of the crisis, see US Business Cycle Expansions and Contractions by the National Bureau of Economic Research.

It still holds true that the largest capacity brackets of 2-3MW and 3+MW are least correlated to electricity prices and therefore depict 'the best' option for investors under the assumption of constant costs to scale and exclusively considering correlations.

Furthermore, I run the linear regression with interaction effects between the financial crisis and production outputs, see Table C.4. Except for the the 2-3MW capacity level, I find no significant interaction effects between the crisis and production outputs.

The results of Table C.4 indicate that the financial crisis does not necessarily play a significant (although numbers are negative) role in the empirical findings of the main analysis. Absolute correlations seem to be relatively constant even when adjusting for the crisis. This is important for investors to consider when allocating capital to wind energy investments or potentially other renewable energy sources. Contrary to what the previous appendix section may suggest, it seems as if correlations between wind energy production and electricity prices are mostly stable throughout crises and could therefore depict a hedge in economic downturns.

Table C.4: Electricity prices, production, and the financial crisis

The table shows the regression results of $p_{i,t} = \alpha + \beta GWh_{i,t} + \omega NBER_t + \gamma p_{i,t-1} + \kappa TWh_t + \upsilon(NBER_t \times GWh_{i,t}) + \sum_{j=1}^{11} \mu_j M_{j,t} + \epsilon_{i,t}$. Specifically, I subset the data sample with respect to capacity levels. The dependent variable is the relevant electricity log-price in area DK1 or DK2, depending on where the individual turbine locates. Production estimates of turbine i at time t are standardized through Equation (1) and documented in GWh. I control for lagged electricity prices (γ) as well as electricity consumption (κ) with the explanatory variable measured in TWh. The interaction term of $NBER_t$ and $GWh_{i,t}$ depicts the correlation of production with electricity prices during the financial crisis as defined by the US Business Cycle Expansions and Contractions by the National Bureau of Economic Research, where $NBER_t$ is a dummy variable that is 1 during the crisis and 0 otherwise. Furthermore, I account for seasonality in price, production outputs and consumption estimates through monthly time fixed effects. Column 6 does not document estimates for the financial crisis and the interaction term because data is available only thereafter. Standard errors are clustered by time and documented in the brackets below the estimates.

	Dependent variable:					
	p_t					
	Total	0-0.5MW	0.5-1MW	1-2MW	2-3MW	3+MW
	(1)	(2)	(3)	(4)	(5)	(6)
β: Turbine Production GWh	-0.441^{***}	-0.376^{***}	-0.638^{***}	-0.323^{***}	-0.262^{**}	-0.291^{**}
	(0.096)	(0.082)	(0.141)	(0.070)	(0.109)	(0.123)
ω: Financial Crisis $NBER$	0.027	0.014	0.019	0.042	0.030	
	(0.052)	(0.043)	(0.062)	(0.053)	(0.051)	
γ: El. Price p_{t-1}	0.765^{***}	0.755^{***}	0.774^{***}	0.773^{***}	0.744^{***}	0.733^{***}
	(0.056)	(0.056)	(0.055)	(0.059)	(0.068)	(0.083)
κ: El. Consumption TWh	0.044^{***}	0.047^{***}	0.041^{***}	0.044^{***}	0.070^{***}	0.090^{***}
	(0.008)	(0.008)	(0.007)	(0.008)	(0.010)	(0.017)
υ: T. Production × F. Crisis	-0.021	0.082	0.038	-0.130	-0.388^{*}	
	(0.266)	(0.186)	(0.328)	(0.266)	(0.213)	
Constant α	0.022	-0.040	0.082	-0.020	-0.404^{**}	-0.714^{**}
	(0.230)	(0.226)	(0.232)	(0.233)	(0.202)	(0.346)
Month fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Observations	585,064	145,896	375,707	36,367	17,763	9,331

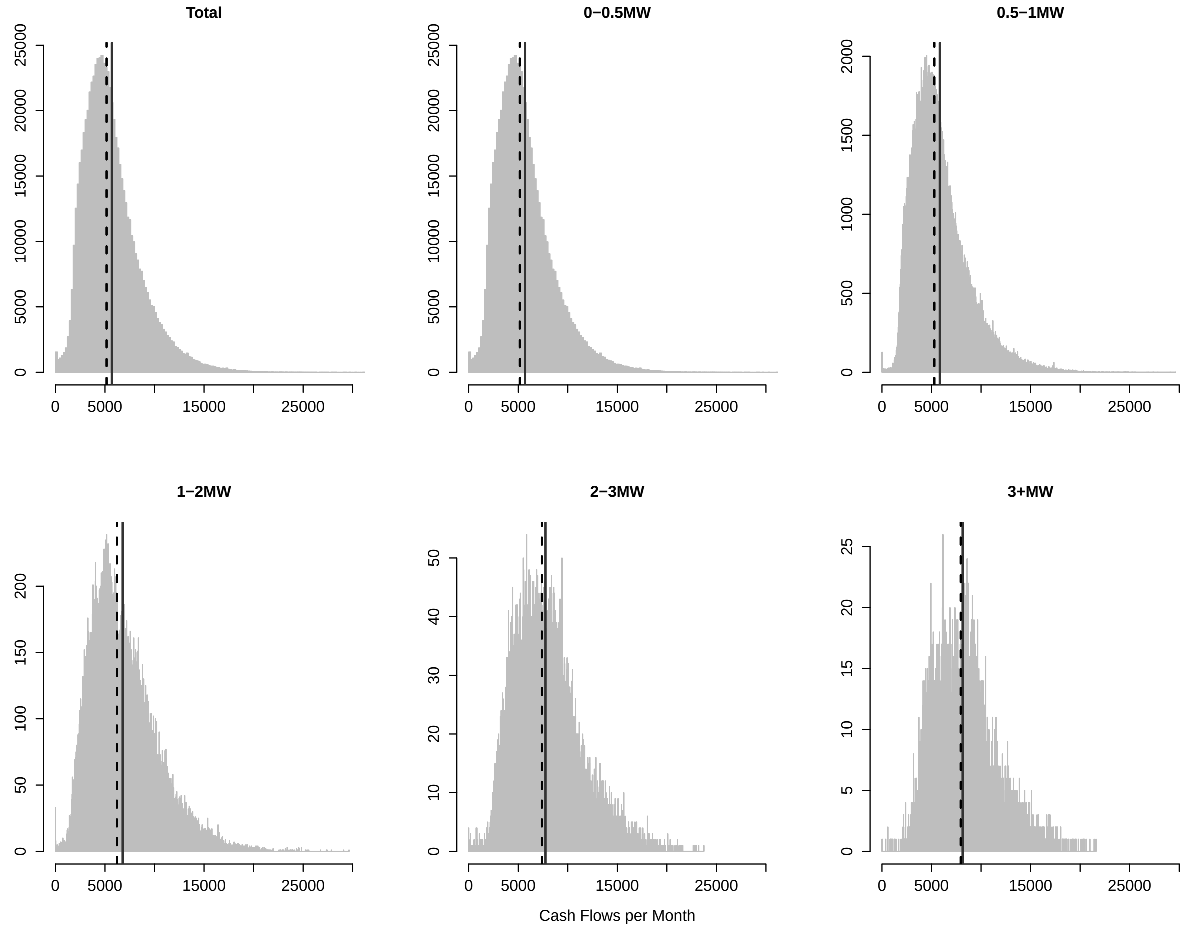
Note: *p<0.1; **p<0.05; ***p<0.01

C.5 Cash flows

In this appendix section, I show what the distribution of cash flows according to $C_t = MWh_t \times P_t$ and under different capacity levels. This implicitly assumes that the correlation between power prices and production is zero within months, so that investors capture the electricity price as denoted by the average price of a given month.

Figure C.3: Cash flows

I calculate cash-flows according to $C_t = MWh_t \times P_t$ for every turbine in the sample. Cash flows are in EUR. Production units of MWh_t were adjusted by capacity levels according to Equation (1). Distributions therefore depict average monthly cash-flows from electricity production for every MW in capacity. The vertical solid line is the mean. The dotted line depicts the median.

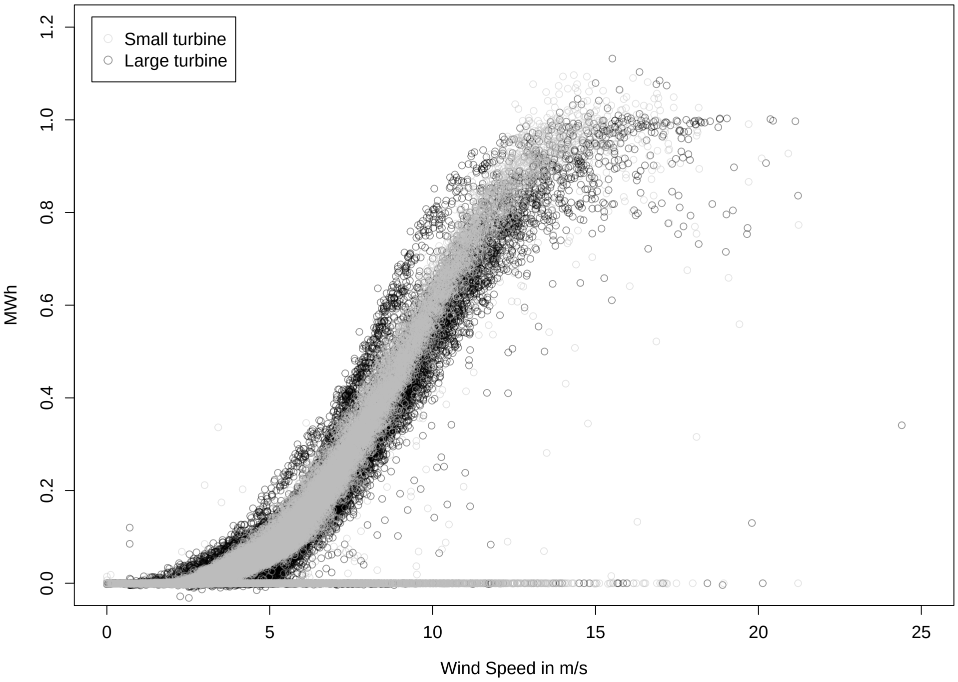


D High-Frequency Data

This appendix section graphically presents the relationship between wind speeds and power production by both a small and a large turbine. The data stems from a private investor in renewable energy.

Figure D.1: High-frequency turbine outputs and wind speeds

This plot shows high-frequency production outputs over wind speeds for an arbitrary small and large turbine each. The data was provided by a private investor in renewable energy. Specifically, the data depicts 10-minute production and output level data, which I aggregate to hourly estimates. I plot a randomly chosen subset of 20,000 observations each for both the small and the large turbine sample. The reason for only showing only a subset of the entire sample is to ensure visibility of the plot. Small turbines are those with a capacity of less than 0.75MW, and vice versa.



Chapter 3

The Value of Renewable Energy and Subsidies: An Investor's Perspective

Abstract

I provide a novel theoretical approach to value wind energy investments. It allows to adjust for a number of risk parameters including wind speeds, electricity price forecasts, discount rates, and uncertainty in subsidies. I use this approach to model wind energy investments under two different subsidy schemes in Denmark through a numerical Monte Carlo simulation. Specifically, I investigate the change from a subsidy scheme under which investors were entitled to receive a fixed premium for a given amount of full-load hours to a tender-based and technology-neutral system. Moreover, I model wind energy investments under the assumption of a subsidy-free asset class. I compare these three systems and expose them to various sources of uncertainty through which I provide more clarity on risk and return considerations of energy investors. Specifically, I find that small structural changes in subsidy compensation schemes could have significant impacts on the decision-making process of capital allocation.

I thank Carsten Sørensen, Ken L. Bechmann, Lars Christian Gaarn-Larsen, Andreas Brøgger, Stefan Hirth, Ramona Westermann (discussant), Kristian Miltersen, Mohamad Afkhami (discussant), the conference participants of the 3^{rd} Commodity Markets Winter Workshop 2019 at the Leibniz University of Hannover, the annual PhD Day 2018 at Copenhagen Business School, the Commodity and Energy Markets Association (CEMA) Annual Meeting 2019 at the Tepper School of Business, the American Finance Association (AFA) Annual Meeting's PhD Poster Session in San Diego, as well as seminar participants at Energistyrelsen and Vestas for helpful comments and discussions. The code developed for the analysis is available upon request. I gratefully acknowledge support from Innovationsfonden and the Pension Research Center. All mistakes are mine.

1 Introduction

This paper proposes a valuation model for wind energy projects with a focus on the Danish market.[1] It combines financial and technical mechanisms that are prevalent when considering investment opportunities. In particular, it combines the production function of turbines with an electricity price forecast model. I utilize this model and apply a numerical example through a Monte Carlo simulation to calculate and compare the value of wind energy projects. Under the base case scenario, I model these projects under no additional subsidy compensation.[2] In an extension, I add two different types of subsidy structures relevant for the Danish market. Finally, I vary a number of key parameters in the model and introduce uncertainty in subsidy distribution to exhibit investors' exposure to different sources of risk.

This study adds to the increasing field of energy finance and contributes to a better understanding of this asset class. Not only in Denmark but across the world the renewable energy sector picks up momentum. Environmental externalities of conventional energy sources stress the importance of rethinking how we produce and utilize energy and how we could transform to a more sustainable economy at large. International agreements as, for example, the Kyoto Protocol[3] are one way to increase awareness of environmental footprints and demand commitment for change. However, there is no universal framework in how to pursue and achieve the goal of cleaner energy production and member countries of these agreements are mostly left alone to adapt. Nonetheless, there is an international understanding that the promotion of more renewable energy sources in particular represents one vital pillar of that journey.

Denmark specifically has committed itself to produce 55% of all electricity through renewable sources by 2030.[4] Wind energy in particular has been a vital contributor to Danish energy production from an early stage, see Figure A.1 in Appendix A. Today, Denmark is considered a pioneer in the industry. Every day, Denmark produces a significant share of its electricity needs through wind energy and even sells its surplus to neighboring countries when production exceeds national demand. Next to other factors as favorable environmental conditions or technical expertise, the excellent standing of the wind energy industry in Denmark today is likely due to generous subsidy schemes, accelerating investment by making the new technology more competitive.

The topic of subsidies is widely discussed among policy makers. The objective is to create

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[1] Denmark is specifically interesting to consider for two reasons. First, it depicts one of the strongest proponents and world leaders of wind energy due to long-time and expansive monetary support of green energy. Second, Denmark has experienced a change in subsidy structures in February 2018, having direct effects on risk and return considerations for future investments in energy infrastructure.

[2] Investors may refer to these types of projects as merchant, that is, future electricity prices are neither hedged nor subject to additional subsidy contributions.

[3] For more information, please see United Nations Climate Change.

[4] For more information, please see Ministry of Foreign Affairs of Denmark.

an effective and cost efficient incentive structure for private capital to consider investment opportunities in renewables.[5] Important stakeholders as, for example, the AURES II project are fully dedicated to finding the right approach to make institutional investors develop and operate new projects. This study contributes to the discussion by providing more clarity to the area of subsidy schemes in renewables and how one can address potential challenges.

This discussion is important as investors very carefully compare subsidy opportunities and other economic and environmental conditions when allocating private capital in green energy infrastructure. This paper proposes a model that incorporates many different factors that are relevant to consider when assessing risk and opportunity in this sector and specifically wind energy. This model can help understand the valuation principles under the variation of various risk parameters. This is possible as the study precisely takes into account the operating principals of wind energy by incorporating them in financial theory. This paper is relevant not only to investors but also from a policy perspective when discussing mechanisms to incentivize private capital to play a bigger role in infrastructure buildout.

Specifically, I aim to investigate the drivers of wind energy risk exposure. In simplified terms, investors yield income based on the following dynamic:

$$Income = Production * (Electricity\ Price + Subsidies) - Operational\ Expenditures \tag{1}$$

In this paper, I investigate the main drivers of uncertainty that come into play when evaluating the equation above. First, I review the production function of wind turbines from a rather technical perspective. I further examine how wind speeds are modeled and thereby develop an understanding of how we can think of energy production through wind.

Second, I review the Danish electricity market over the past four years and utilize a common way how investors could think of spot prices in the future. By definition, electricity depicts the one and only commodity that wind energy producers sell and thereby represents the only source of income for investors when neglecting additional subsidies.[6] In particular, I review the Nordpool System (SYS) spot market price for electricity from 2014 until the end of 2017, denoted in Euro (Figure 2). I use historical data to forecast electricity prices over a time horizon of 25 years through methods by Lucia and Schwartz (2002) and Seifert and Uhrig-Homburg (2007). My forecast for

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[5] For example, the consultancy agency Copenhagen Economics points out that next to understanding technologies in detail, one also needs to forecast capacity mixes, power price developments, or take into consideration taxation schemes.

[6] I do not consider other types of incomes or investment incentives as, for example, tax credits that some investors might have in other markets. Nevertheless, these other types of incentive structures can just as well be relevant for renewable energy investment considerations.

the Danish electricity price incorporates a seasonal pattern over different periods of the year as well as a stochastic part, which adds both mean-reversion and a jump component to the time series simulation. Although this forecast intends to first and foremost serve the valuation purpose of the model, it also sheds light on electricity price patterns in the market. In another step, I further consider correlation dynamics between energy production and electricity prices. Generally speaking, market prices tend to be higher when renewable energy production is high, and vice versa, which needs to be accounted for.

In another step, I review subsidies in the Danish renewable energy industry for two reasons. First, I aim to value wind energy investments as a whole, meaning that subsidies as a part of cash flows must be considered. Secondly, the paper values their share as part of an investment opportunity in its entirety. I examine subsidies in wind energy under no uncertainty as well as under uncertainty by considering future subsidy cut probabilities.[7] All of the above provide a better understanding on how regulatory changes may affect asset prices. In particular, I consider two subsidy systems in this study. The first one, I call the *old* subsidy system, which is what investors in Denmark were subject to up until 20.02.2018. Under this old subsidy system, onshore wind energy investors were entitled to subsidy compensation that guaranteed them 25øre/kWh (33.5€/MWh) for the first 22.000 full load hours on top of 2.3øre/kWh (3.1€/MWh) balancing costs for electricity over the lifetime of a project.[8]

The second subsidy system I consider, I refer to as the *new* subsidy system, which is what Denmark has implemented as the successor to the expired system. Specifically, the new subsidy system depicts a tender-based and technology-neutral approach. The procedure is such that investors intending to develop a new wind farm can place a bid at a yearly auction for receiving a fixed subsidy on top of the market price of electricity. The maximum bid is capped at 13øre/kWh. The budget is constrained to 254mDKK (34m€) in 2018 and 579mDKK (78m€) in 2019. If accepted, the additional compensation is granted for a time-horizon of 20 years. One auction each takes place in 2018 and 2019, in which the lowest bids are accepted until the given budgets run out.[9] Moreover, I consider wind energy investments under no additional compensation through subsidies, allowing me to compare and evaluate the two systems against the assumption of a subsidy-*free* investment opportunity as a base case scenario.[10] The model proposed by this paper could, however, implement any other subsidy system and value their share as part of the investment. In fact, the final

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[7] Please note that even though many investment professionals might refer to the indicated subsidies as a type of feed-in-tariffs, I tend to stick to the term of subsidies throughout the study.

[8] Based on the law under the Promotion of Renewable Energy Act.

[9] For more information, see WindPowerMonthly and Energistyrelsen. Table E.1 in Appendix E further shows the results of the first tender in 2018.

[10] This subsidy-free scenario is becoming more relevant in light of the development that many countries decrease or entirely abandon subsidy incentives.

section of my results shows how one can utilize the model for an entirely different subsidy scenario.

Lastly, I review the cost structure of wind energy investments. This includes maintenance costs over time as well as initial capital expenditures. As costs are not examined as a source of uncertainty in this framework, I take them as certain and do not consider unforeseen additional costs or other expenditures (e.g. repair costs).[11]

In a final step, I combine all income drivers as outlined in Equation (1), constructing a model to forecast cash flows from wind energy investments. I apply this model to a numerical example and put a hypothetical investment opportunity to the test. In particular, I assume an average-sized wind turbine and run a Monte Carlo simulation predicting risk and return patterns. I discount the simulated cash flows to generate present value estimates and compare them to initial capital expenditure estimates of similar projects. Furthermore, I vary a selection of parameters to examine the investment opportunity's exposure to its unique sources of risk. Next to a variation in wind speeds (i.e. production outputs), electricity price forecasts, and discount rates, this includes the consideration of subsidies under uncertainty. Furthermore, I compute an equilibrium bid under which the new and old subsidy system would be equally profitable and thereby add to the discussion of future subsidy system proposals.

I make three hypotheses. First, I expect to see renewable (wind) energy investments to document lower returns under the new subsidy compensation structure. This is because I project realized subsidy compensation to be significantly below the maximum bid and therefor less profitable. Second, I anticipate wind energy to be much less favorable under no additional subsidy scheme and to be barely profitable. Third, I presume the assumption of uncertainty in subsidy compensation to play a significant role in the decision-making process of the allocation of capital towards renewable energy. If there is indeed a real concern that subsidies are adjusted throughout the anticipated time of eligibility, a favorable investment today might turn into an unfavorable one tomorrow.[12]

The remainder of this paper is structured as follows. A literature review outlines related research. Section 2 describes the value drivers in wind energy investments and combines them in a model. Section 3 lays the groundwork for the simulation of an investment opportunity under varying assumptions. Section 4 shows the results. Finally, Section 5 concludes the paper.

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[11] This reflects reality in the way that investors tend to be less concerned about operational expenditures over time as they are likely to be minor. Even if substaintial maintanance repairs are necessary due to technical failures, insurances often hedge such risks.

[12] For example, Spain, in 2011, cut its feed-in-tariffs for solar photovoltaic energy, provoking substantial losses for investors. Such practices have severe consequences as outlined by the Financial Times (2011): Renewable energy: Subsidy cuts cause crisis of confidence.

Literature review

This paper's objective is to shed light on the quantification of relevant drivers for risk and return in wind energy investments.[13] I aim to utilize a number of concepts from not only the area of financial economics, but also some that rather relate to technical fields. For example, I adopt the unique wind plant power curve to approximate energy outputs (Wan et al., 2010).[14]

Another vital concept applied in this study revolves around the forecast of electricity prices. Typically, prices fluctuate heavily and according to the demand in different times of the day, weekdays and seasons, see Villaplana (2003) or Escribano et al. (2011). However, not only short-term prices but also long-term trends significantly matter for investors as Barcelona (2017) points out. To forecast electricity prices, I utilize an approach by Lucia and Schwartz (2002) and Seifert and Uhrig-Homburg (2007) and apply it to historical Danish electricity spot prices. I additionally incorporate empirical findings on the negative correlation between electricity prices and renewable energy production, e.g. Cutler et al. (2011), Rathmann (2007) or Würzburg et al. (2013).

This paper contributes to the existing literature in many ways. It develops a model for the valuation of wind energy assets that is not only applicable to the Danish industry as it is easy to adjust to other markets and subsidy systems too. Specifically, this can be done by utilizing power prices from respective markets to estimate the model's paramaters and by adjusting subsidy compensation structures. To my knowledge, no comparable study approximates income from wind energy in a similar and hands-on manner. It allows for the variation of relevant risk parameters and can easily adjust to different geographical locations and turbine specifications.

2 Methodology

This chapter outlines the approach to simulate income (I_t) of wind turbines under risk and uncertainty, which it then applies to forecast cash flows for a hypothetical wind energy investment in Denmark under different scenarios. The results provide a better understanding on the relevance of chosen risk parameters as well as the value and a comparison between subsidy schemes. In short, I predict future cash flows based on the four components of Equation (1). These include production outputs in MWh_t, the electricity price P_t, subsidies S_t^{Old} and S_t^{New}, respectively, as well as operational costs C_t, all at time t, where Δt represents daily increment counts. Defining these four components one by one allows to take into account uncertainty through the variation

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[13] These types of investment vehicles fall into the category of real investments. Concepts of this paper's framework adopt on concepts of the evaluation of investment opportunities as discussed by Dixit and Pindyck (1994).

[14] The production units used for this study are megawatt-hours (MWh), where 1MWh equals 1000kWh. The only source of uncertainty in production is wind speeds. Related literature suggests that wind speeds are most precisely characterized by a Weibull distribution (Gryning et al., 2016). Figure B.1 in Appendix B exhibits a typical probability density function of a Weibull distribution and how it is applied to model wind speeds.

of single risk parameters. Sensitivity analyses of these relevant risk parameters add to a granular perspective risk and opportunity in the asset class.

The remainder of this chapter is organized as follows. First, I derive the production function of wind turbines. Second, the study examines the electricity spot price from 2014 until 2017 and, based on Lucia and Schwartz (2002) and Seifert and Uhrig-Homburg (2007), reviews and later applies a forecasting method. Third, I define the two different subsidy systems and necessary assumptions as processes with and without incorporating uncertainty. Moreover, I review the maintenance and operating costs of wind energy production. Finally, the study puts together all four parts, defines a hypothetical investment in a wind turbine, and simulates income in the spirit of Equation (1) over a time horizon of 25 years. The combination and partial substitution of all components allows to review wind energy investments from a risk and return relationship, and further distinguishes and compares between different subsidy schemes.

2.1 Wind energy production

The right estimation of wind energy production is complex and something engineers have spent years on in order to approximate outputs as precise as possible.[15] As for all wind energy projects, the approximate output of Megawatt-hours (MWh_t) follows the production function of Figure 1, expressed in Equation (2). The parameters ρ, A, V, and C_p define the air density, rotor area, wind speed and the power coefficient.[16] Specifically, the production output of wind energy can be approximated as follows:

$$MWh_t = f(V_t) = \begin{cases} min\left[\frac{1}{2}\rho A V_t^3 C_p 10^{-6}; MW_{max}\right] * h & \text{if } V_{min} \leq V_t \leq V_{max} \\ 0 & \text{if } V_{min} > V_t > V_{max} \end{cases} \tag{2}$$

Electricity production starts at a given cut-in speed V_{min} and stops at the cut-out speed V_{max}, meaning that before V_{min} and after V_{max} there is no energy output. In between, production first increases steeply until it reaches a maximum productivity level of MW_{max}, see Figure 1. The parameter h depicts the number of hours the wind turbine operates a day.[17]

As mentioned above, the power output per day can be expressed as the function of wind $f(V_t)$. V_t is the only random variable and changes at time t, following a Weibull distribution. The Weibull distribution calls for an estimation of the scale and shape parameters A and k, see

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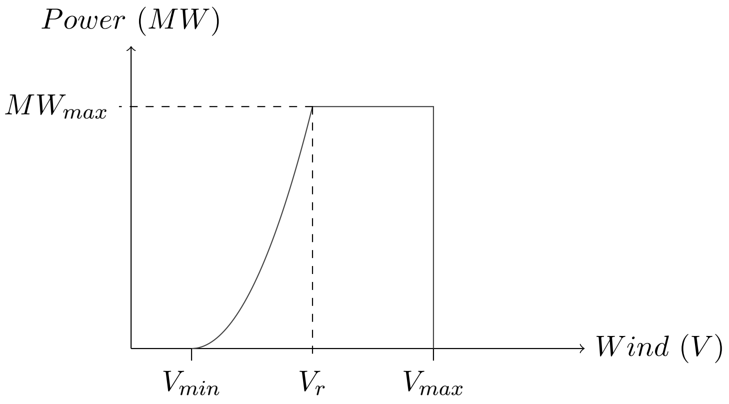
[15] Many Danish producers rely on estimates given by calculations by the Danish Wind Industry Association.

[16] For more information, see Yu and Tuzuner (2008) and a note by npower renewables. The final equation was developed with the support of my supervisor Lars Christian Gaarn-Larsen.

[17] Please note that the power function (2) derived for this paper serves as an approximation for power outputs and is applied because of its easy implementation. The even more precise power function slightly deviates from the Equation (2) and Figure 1, but due to its increased complexity and only incremental improvement is not utilized within this framework.

Figure 1: Power generation

This graphs illustrates Equation (2), neglecting h, to determine energy output. Wind, V, is measured in m/s. V_{min} and V_{max} are commonly referred to as the cut-in and cut-out speed, respectively. V_r depicts the rated wind speed, where the turbine reaches its maximum production capacity and produces MW_{max}.



Appendix B. I apply a similar methodology as Johnson et al. (2005) to simulate average daily wind speeds. Gryning et al. (2016) note that Weibull distributions are typically used for the estimation of hourly wind speeds. In this framework, however, it serves as an estimation for average daily wind speeds.

2.2 Electricity prices

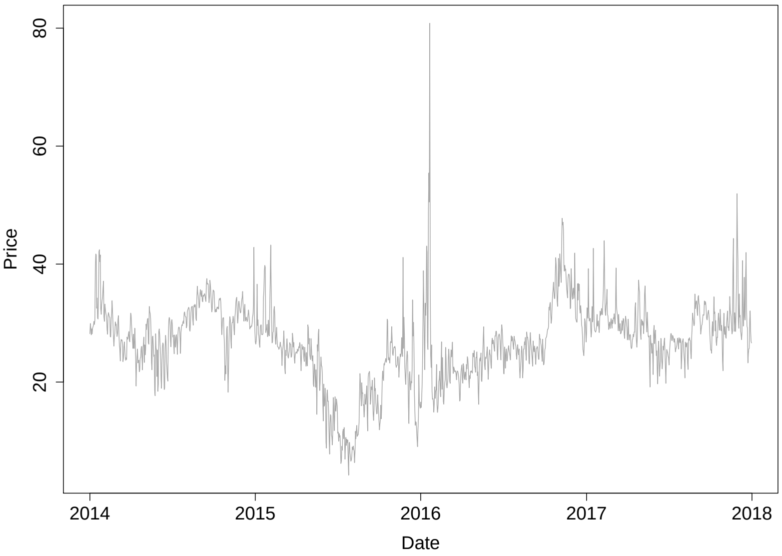
Another vital component of income from wind energy investments is electricity price levels. I use historical data to derive parameter estimates to forecast electricity spot prices, and later apply as part of the investment valuation of a Danish wind turbine. Specifically, I obtain hourly electricity spot prices from the Nordic electricity market irrespective of capacity congestion in the individual interconnections between the areas of Denmark, Sweden and Germany (referred to as SYSTEM), see Energi Data Service.

First, I average hourly prices over each day to obtain daily prices, see Figure 2. The obtained spot prices are highly volatile not only in the given time-series but also over longer horizons, an observation for other electricity markets as well. Various spikes lead to high and significant short-term price volatility. Furthermore, there are seasonal movements in the data, meaning that prices vary across different seasons of the year. This comes as no surprise assuming that households demand less (more) electricity in the summer (winter), supporting previous findings in the literature, e.g. Lucia and Schwartz (2002), Seifert and Uhrig-Homburg (2007), Villaplana (2003) or Escribano et al. (2011).

The numerical application requires to forecast electricity prices for a time horizon of 25 years. I choose a mean-reverting model with seasonality and a jump component in the spirit of Lucia

Figure 2: Electricity price in the Nordic market

The graphic captures daily spot prices of the Nordic electricity market irrespective of capacity congestion in the individual interconnections between the areas of Denmark, Sweden and Germany (referred to as SYSTEM). The price is denoted in EUR per MWh. *Source:* Energi Data Service.



and Schwartz (2002) and Seifert and Uhrig-Homburg (2007). It uses historical data to estimate the required parameters. As the estimation period is very long and regimes might change to large degrees throughout time, I must stress that this forecast merely serves as an approximation and does not attempt to confidently forecast the electricity spot price for the time horizon in question.

Lucia and Schwartz (2002) investigate historical data from the Nordic Power Exchange and note three important characteristics of electricity spot prices. First, they contain jumps that occur in times of high demand or little supply. Most times however, prices quickly return to an average level. Finally, they exhibit a seasonal pattern throughout the year. Visible in Figure 2, spot prices are typically higher (lower) in cold (warm) seasons due to a variation in demand. They note that the changes in climate in different seasons lead to shifts in the demand for heating and thereby demand for electricity.

Acknowledging these empirical facts, a process is split in two parts, a deterministic function of time that captures seasonal patterns and a diffusion stochastic process that incorporates mean-reversion and jumps. Following Seifert and Uhrig-Homburg (2007), the logarithm of the spot electricity price P_t is expressed as follows:

$$\ln P_t = f(t) + X_t \tag{3}$$

The components $f(t)$ and X_t depict the deterministic seasonal part and the stochastic part, respectively. The seasonal component is modeled based on

$$f(t) = s_1 \sin(2\pi t) + s_2 \cos(2\pi t) + s_3 \sin(4\pi t) + s_4 \cos(4\pi t) + s_5 + t\mu, \tag{4}$$

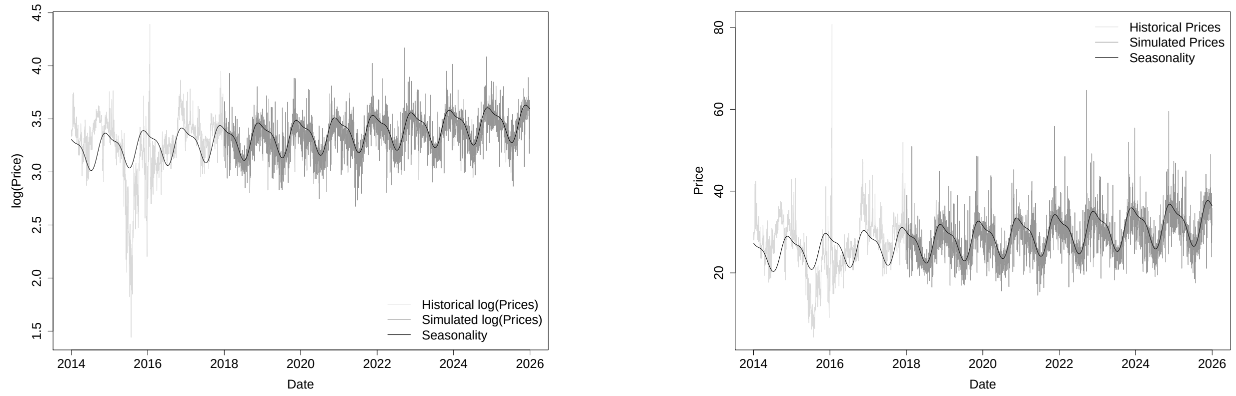
where $s_1, ..., s_5$ are constant parameters and μ is the drift in the seasonality estimation. Therefore, μ captures the expectation in long-run average price developments. As in Seifert and Uhrig-Homburg (2007), X_t captures a mean-reverting Ornstein-Uhlenbeck process with jumps:

$$dX_t = (\alpha - \kappa X_t)dt + \sigma_X dW_t^X + \xi_t dJt \tag{5}$$

Here, α and κ are mean-reversion parameters; σ is the volatility, and W_t^X depicts a standard Brownian motion. J_t captures a Poisson process with a jump intensity of λ_J and is normally distributed with a jump size of $\xi_t \sim N(\mu_\xi, \sigma_\xi)$. This model is considered not only by Seifert and Uhrig-Homburg (2007), but many others, as, for example, Villaplana (2003) or Escribano et al. (2011). The procedure goes as follows. First, the deterministic seasonality part is computed through the least squares method. The seasonality part is then removed from the time series and the stochastic part is calibrated through maximum likelihood estimation. I then use the estimated parameters, documented in Table 1, as the basis for forecasting electricity prices over 25 years. Figure 3 provides the output of one single simulation.[18]

Figure 3: Electricity price forecasts

Figure 3a exhibits the seasonality in the Nordpool System (SYS) spot market log(price) from 2014 until the end of 2017 on a daily basis. After 2017, prices are forecasted applying Equation (3) and using estimates from Table 1. Figure 3b reflects the real historical and forecasted prices in EUR/MWh.



(a) Log prices and forecasts

(b) Prices and forecasts

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[18] Furthermore, Appendix C documents how the distributions of historical data compare to the simulated data.

Price vs. production

A number of studies document a negative causal relationship between renewable energy production and electricity prices, e.g. Cutler et al. (2011), Rathmann (2007) or Würzburg et al. (2013). The argument is that increased renewable energy production shifts the supply curve to the right, resulting in a lower equilibrium price. The size of this effect, however, is controversial (Würzburg et al., 2013).

I test this effect in the Danish market by a simple regression approach. I download data on Danish wind energy supply from Nord Pool AS and regress the log-price of electricity against daily aggregated wind energy supply.[19] I define production as the total output in day t over the average of the time series. Table C.1 Appendix C displays the results.

Though minor, I find a significant negative coefficient of production on daily electricity log-prices of approximately -0.045. Even when controlling for lagged prices, this coefficient stays constant. Because the objective is to invent a realistic and hands-on income and valuation model, it needs to take this stylized fact into account. If the negative causality would instead be neglected, future income forecasts would be overestimated. I therefor add a factor β to Equation (3), correcting for the negative correlation between production and energy market prices. This means that realized prices follow

$$\ln P_t = f(t) + X_t + \beta \frac{f(V_t)}{f(\overline{V})} \tag{6}$$

The factor of β captures the economic effect of the daily electricity output on the price that the investor receives for his supply. Even though, this effect is minor at first sight, it impacts the total income generated by the investor significantly. Also, in light of more renewable energy investments in the future, this causality might strengthen due to the increased volatility in supply as an effect of changing wind speeds and also the inability of energy storage.

The absolute effect is larger for high production times, and vice versa. By default, it changes the realized price series of electricity, however, it is not to be seen as an extended version to Seifert and Uhrig-Homburg (2007). It rather adds to the discussion in the industry on baseload versus capture prices.[20]

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[19] Data can be accessed through Nord Pool Historical Market Data.

[20] Baseload prices are observed prices in the market. Capture prices are what a projects actually realize. For example, if production is high when prices are low, and vice versa, the realized price is below the observed average electricity price.

2.3 Subsidies

Apart from the income generated through the market price of electricity, investors are compensated with an additional premium paid per MWh they produce and feed into the grid, an incentive set by the government for investors to engage in renewable energy technologies and make them competitive with cheaper conventional energy sources. This study considers two different subsidy systems and refers to them as an old and a new system. In addition, I also consider the case of no subsidies throughout the analysis. The old system ran out on the 20.02.2018, whereas the new system depicts the successor put in place by the Danish authorities in alliance with the European Union's regulatory requirements.[21] After reviewing the general mechanics of the two major types of subsidy systems, both the old and the new system are outlined in greater detail and expressed as processes to incorporate them in the income model and as part of Equation (1). In a second step, I additionally consider uncertainty in subsidy compensation to examine another source of financial risk exposure in the subsequent numerical implementation.

Subsidy structures

Subsidies in renewables create incentives for investors to allocate capital to them through increasing risk-return ratios. They help make these investments more attractive, especially in their competition with conventional energy sources, and are typically referred to as feed-in-tariffs. This chapter depicts a short review of the two general types of feed-in-tariffs as found in a number of countries.[22] Specifically, one is referred to as a fixed premium system, whereas the other relates to a variable premium system.

The fixed premium system subsidizes investors with additional top-ups regardless of what they already yield in cash flows from current electricity prices. For every produced MWh, they earn an additional fixed premium for a predetermined period of time (or number of MWhs). In particular, they earn

$$C_t^{FP} = P_t + S_t^{FP}, \tag{7}$$

where C_t^{FP} is the cash flow at time t under the fixed premium (FP) system. P_t and S_t^{FP} are the electricity price and the level of the premium at time t. As mentioned, the level S_t^{FP} is likely constrained by time or alternatively by the number of production hours.[23] Figure 4a shows the

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[21] See WindPowerMonthly.

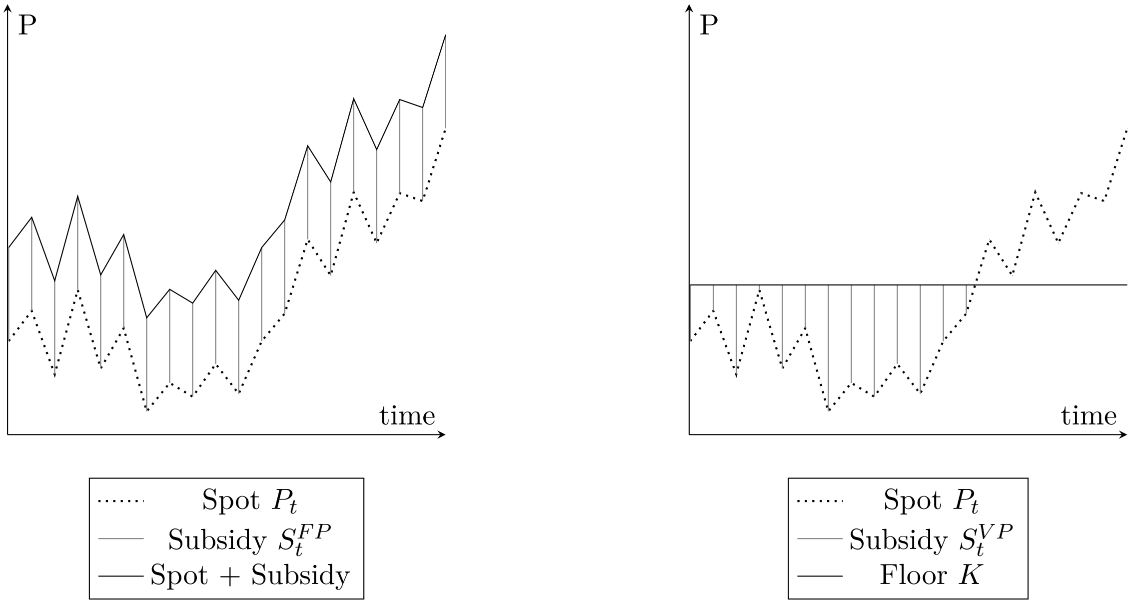
[22] Find information on subsidy schemes across European countries in the RES LEGAL Europe database.

[23] Please note that the documentation on subsidy structures above provides general cases only. Typically, countries adopt these general mechanics of subsisy structures subject to additional constraints or specifications. There could be time, production, or other technical constraints and limitations to the eligibility or level of either fixed or variable premium systems.

mechanics of fixed premium systems.

Figure 4: Subsidy systems in comparison

I show the mechanics of feed-in-tariffs under fixed and variable premium systems. Figure 4a shows the fixed premium system under which investors receive an additional premium to the current market price of electricity. Figure 4b documents the variable premium system under which investors are guaranteed a minimum level of compensation (K) for every production unit.



(a) Fixed premium

(b) Variable premium

The variable premium system one the other hand depends on the current level of electricity prices. In essence, investors are guaranteed a minimum price level of electricity. Whenever the current price of power exceeds the guaranteed price level, there are no distributions of additional subsidy compensations. When the price level of electricity is very low, however, the additional premium is high. The ability to always sell electricity at a minimum level can be considered as an option-like feature under which investors yield cash flows of

$$C_t^{VP} = \begin{cases} P_t + S_t^{VP} & \text{if } P_t < K \\ P_t & \text{if } P_t \geq K, \end{cases} \tag{8}$$

where C_t^{VP} is the cash flow at time t under the variable premium system (VP). The minimum price level (floor) of electricity the investor is guaranteed is K, which one could think of as the strike. In the case where $P_t < K$, the cash flow at time t is determined by the sum of the electricity price S_t^{VP} and the premium P_t, which always equals K (or put differently, the subsidy level at time t equals $S_t^{VP} = K - P_t$). Whenever $P_t > K$, the investor only yields the current level of P_t

for every MWh he sells; there is no additional compensation. Alternatively, the investor can think of the payoff at time t as $C_t^{VP} = max[P_t, K]$.[24] Figure 4b presents the fixed premium system graphically.[25]

Denmark, generally speaking, has adopted a type of a fixed premium system as their chosen subsidy to create incentives for investors to allocate capital to green energy. Both the old and the new system rely on the same mechanics but differ in their specifications with respect to levels, duration, and other constraints. One key objective of this study is to better understand the differences in risk and return dynamics in the change from the old to the new system.

Even though, this study focuses on a fixed premium system as observable in Denmark, one can adjust the framework to variable premium systems also. In the final section of the results, I apply a theoretical case of a variable premium system, in which case the definition of subsidy payoffs changes within the model and in line with Equation (8).

No uncertainty in subsidies

Referred to as the old subsidy compensation system, producers who commissioned projects until 20.02.2018 are compensated with 25øre/kWh (33.5€/MWh), represented by G, for 22.000 full load hours on top of 2.3øre/kWh (3.1€/MWh), denoted by B, balancing costs for electricity over the entire lifetime of the project. As discussed in the previous subsection, this is a type of a fixed premium system and can be defined as

$$S_t^{Old} = \begin{cases} G + B & \text{if } \sum_{j=1}^{t} f(V_j) \leq 22.000h * MW_{max} \\ B & \text{if } \sum_{j=1}^{t} f(V_j) > 22.000h * MW_{max} \end{cases} \tag{9}$$

Note that, in this definition, there is no consideration of uncertainty in subsidy distributions. Investors assume that they will be granted the full subsidy stream throughout the project's eligibility, see Figure 5a.

The new subsidy system is that of a tender (but still a type of a fixed premium system). Investors can place bids on receiving subsidies per MWh at yearly auctions. The lowest bids are granted to investors until funds for each tender are exhausted. The bids must not exceed 13øre/kWh (17.4€/MWh). If granted the tender bid, the subsidy premium is paid on top of the market price over a time horizon of 20 years ($t = 20 \times 365 = 7300$ days):

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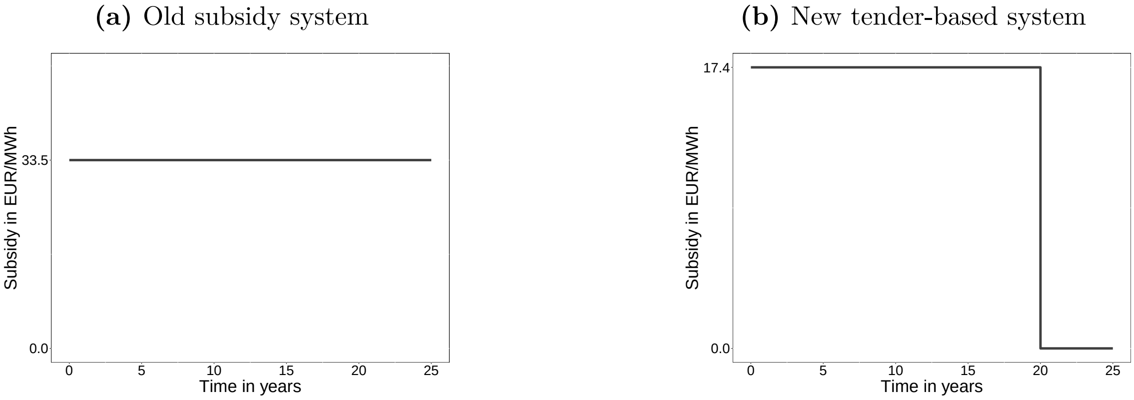
[24] A policy maker might adjust this subsidy scheme in a number of ways. For example, there could be caps and floors to the premium level, so that the total premium at every time instance is constrained (e.g. sliding premium). In this case, the total cash flow yielded at time t could be below K. Other constraints could, for example, relate to technological requirements, time limits, or total payouts of subsidies.

[25] For more information on feed-in-tariffs and feed-in-premiums see, for example, Kitzing and Ravn (2013), Kitzing (2014) or Farrell et al. (2017).

Figure 5: Subsidies under no uncertainty

Figure 5a depicts the old subsidy scheme in which investors are paid 33.5€/MWh until they have produced 22.000 full-load hours. It drops to 0€/MWh after, which is typically the case 5-7 years into the project. Figure 5b exhibits the new subsidy tender system, under which investors place bids on the subsidy compensation they would like to receive for each MWh. The bids must not exceed 17.4€/MWh and are granted for a time horizon of 20 years. The lowest bids are accepted until the given budget runs out.


(a) Old subsidy system

(b) New tender-based system

$$S_t^{New} = \begin{cases} S^{New} & \text{if } t \leq 7300 \\ 0 & \text{if } t > 7300 \end{cases} \tag{10}$$

Formula (10) expresses the bid that investors place as S^{New}. As in the old subsidy scheme, investors assume no uncertainty in this framework. They are entitled to their bid, if granted, over the project's first 20 years and assume them to be distributed with certainty, see Figure 5b.

Uncertainty in subsidies

In this section, I add uncertainty in subsidy distributions over time to conduct additional sensitivity analyses. Specifically, I assume that with a given probability, policy makers impose subsidy cuts, affecting the expected cash flows from the investment and therefore its risk exposure. In detail, I redefine S^{Old} and S^{New} as the updated processes that incorporate a risk parameter called λ.

In particular, the old subsidy scheme as in Equation (9) changes in a way that G_t, now dependent on time, is considered to be uncertain in the future:

$$S_{t+1}^{Old} = \begin{cases} max\left[G_t - \tilde{\varepsilon}_t(N_{t+1} - N_t); 0\right] + B & \text{if } \sum_{j=1}^{t+1} f(V_j) \leq 22.000h * MW_{max} \\ B & \text{if } \sum_{j=1}^{t+1} f(V_j) > 22.000h * MW_{max} \end{cases} \tag{11}$$

I assume that investors predict future cuts in these subsidies, meaning that the state will not respect its commitment to compensate them as agreed. The variable G_t, under this new assumption, follows a jump process, where N_{t+1} is defined as

$$N_{t+1} = N_t + \begin{cases} 1 & \text{with probability } \lambda^{Old}\Delta t \\ 0 & \text{with probability } 1-\lambda^{Old}\Delta t \end{cases} \tag{12}$$

The probabilities are defined as

$$Prob(N_{t+1} = N_t + 1) = Prob(z_{1t} \leq z_\alpha) = \lambda^{Old}\Delta t \tag{13}$$

$$Prob(N_{t+1} = N_t) = Prob(z_{1t} > z_\alpha) = 1 - \lambda^{Old}\Delta t \tag{14}$$

The parameter of $\tilde{\varepsilon}_t$ captures the magnitude of the jump that is realized if triggered and is computed as

$$\tilde{\varepsilon}_t = \left| u_o + u_1 z_{2t} \right|, \tag{15}$$

where u_0 depicts the constant average jump in subsidies. The parameter of u_1, another constant, is multiplied by a standard normally distributed variable of z_{2t} and thereby adds uncertainty to the jump's magnitude. The jump value of Equation (15) is strictly positive, meaning that subsidy compensations cannot increase but only decrease over time. Furthermore, there is no uncertainty in the constant of B. G_0 in Equation (9) equals 25øre/kWh (33.5€/MWh) as the old subsidy scheme's starting point.

I redefine the new subsidy compensation system and incorporate uncertainty through

$$S_{t+1}^{New} = \begin{cases} max\left[S_t^{New} - \tilde{\upsilon}_t(M_{t+1} - M_t); 0\right] & \text{if } t < 7300 \\ 0 & \text{if } t \geq 7300 \end{cases} \tag{16}$$

The likelihood of future cuts in the subsidy level investors were granted at the auction follows the same process as in Equation (13) and (14):

$$M_{t+1} = M_t + \begin{cases} 1 & \text{with probability } \lambda^{New}\Delta t \\ 0 & \text{with probability } 1-\lambda^{New}\Delta t \end{cases} \tag{17}$$

The probabilities follow

$$Prob(M_{t+1} = M_t + 1) = Prob(z_{3t} \leq z_\alpha) = \lambda^{New}\Delta t \tag{18}$$

$$Prob(M_{t+1} = M_t) = Prob(z_{3t} > z_\alpha) = 1 - \lambda^{New}\Delta t \tag{19}$$

I assume the magnitude of the jump $\tilde{\upsilon}_t$ to be

$$\tilde{\upsilon}_t = |q_o + q_1 z_{4t}|\,, \tag{20}$$

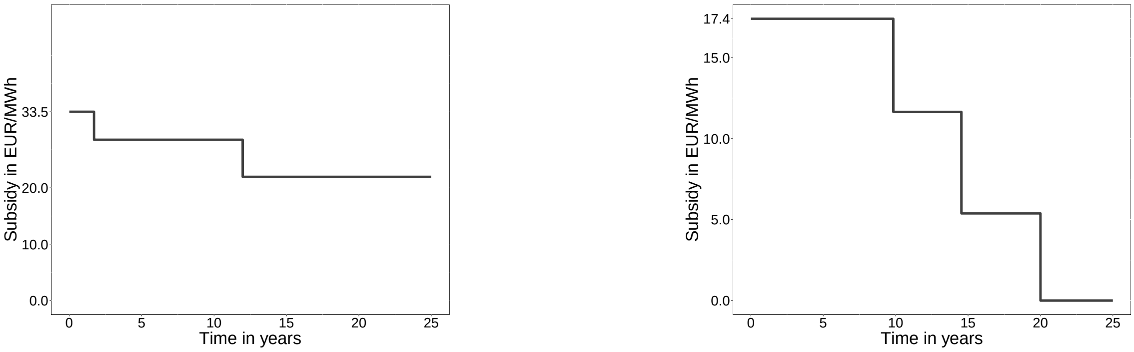
where q_0 depicts the constant average jump under the new subsidy system and q_1 adds uncertainty to the jump's magnitude by being multiplied with the standard normally distributed variable of z_{4t}. Starting off, S_0^{New} is 17.4€/MWh, which represents the maximum bid in the new tender-based system.

The variables of $z_{1t}, ..., z_{4t}$ are standard normally distributed random variables of $z_{it} \sim N(0,1)$. Furthermore, Δt equals $\frac{1}{365}$, so that λ_t^{Old} and λ_t^{New} document yearly probabilities.

Figure 6 shows what a subsidy cut path could look like in the model. Investors yield lower income in the future if subsidy cuts materialize, lowering the present value, i.e. returns, of their investment.

Figure 6: Subsidies under uncertainty

Both graphs represent sample paths of subsidy compensation streams under uncertainty. The yearly probability of subsidy cuts, denoted by λ^{Old} and λ^{New}, equals 10%. In Figure 6a, investors are subject to the old subsidy system with 33.5€/MWh at time $t = 0$. Thereafter, S_t^{Old} depends on how subsidies develop under uncertainty. Investors are then compensated with S_t^{Old} at each time instance t until they have produced 22.000 full-load hours. It drops to 0€/MWh thereafter, which is typically the case 5-7 years into the project. Figure 6b exhibits the new tender-based subsidy compensation scheme, under which investors place bids on the subsidy compensation they want to receive for every MWh. These bids must not exceed 17.4€/MWh and are granted for a time horizon of 20 years. This scenario assumes investors are compensated with the maximum bid of 17.4€/MWh at $t = 0$ but are exposed to subsidy cuts thereafter.



(a) The old subsidy system

(b) The new tender-based system

2.4 Operating costs

Finally, I assume no uncertainty in operating costs over time. I project yearly total costs for operation and maintenance and divide them among the total days of each year:

$$C_t = C_{yearly}\Delta t \tag{21}$$

Next to these continuous and systematic operating expenditures, investors might face unforeseen costs over the lifetime of a project such as repairs or the exchange of broken equipment. However, this seems to happen only rarely in the industry. Also, most investors possess insurances against potential damages that might occur throughout operation. Additionally, investors tend to own guarantees from the seller of turbines (or their individual parts).

For this reason as well as considering that this study's objective primarily revolves around the comparison of different subsidy schemes and the value of renewable energy at large, I neglect these rare instances of unforeseen additional operating expenditures. Instead, I focus on parameters which are subject to much greater uncertainty, including subsidy distributions, wind speeds (e.g. production), or electricity prices. Nevertheless, one could adjust this definition of operating costs within the model's framework and also include the probability of large unforeseen additional expenditures.

2.5 Income and present value estimation

The previous sub-chapter exhibited all relevant constituents that add to the income generated by wind energy investments. These include production, electricity prices, subsidies and costs. This study's objective is to put these constituents together in a universal framework, model wind energy investments under varying assumptions and compare and value different subsidy schemes. I define a hypothetical wind energy investment, simulate income streams, discount the resulting cash flows and sum them up to present values.

Specifically, income at time t based on Equation (1), follows

$$I_t = MWh_t(P_t + S_t) - C_t \tag{22}$$

Utilizing this equation, I compute incremental incomes for each day t ($t = 1, 2, ..., T$) of the investment's lifetime. I discount all incomes by a risk-adjusted discount rate of 7%, see Table 1, and sum them up to calculate present values (PV).[26] In a later application, I vary this risk-adjusted

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[26] Discussions with industry professionals revealed that 7% is widely considered as a hurdle rate to consider the investment into a renewable energy asset.

discount rate as part of a sensitivity analysis.

The ratio of $PV/CAPEX$ then determines whether the investment can be considered as favorable. If $PV/CAPEX > 1$, investors will see the investment opportunity as profitable, and vice versa (Bodie et al., 2009). A sensitivity analysis will further expose what impact changes in selected parameters, for instance the probability of subsidy cuts, have on investment opportunities.

3 Simulation

The valuation model outlined in the previous chapter calls for a numerical application under different scenarios and uncertainty assumptions. The results value wind energy investments, their exposure to asset-specific risks and subsidy compensation. Specifically, I apply a Monte Carlo simulation to draw outcomes for the ratio of PV/CAPEX. First, I run a base case scenario, which computes the ratio distribution under one explicit numerical definition of variables. Secondly, I vary the wind speed scale parameter A, the drift in the electricity price μ, and the discount rate r. Moreover, I determine an equilibrium bid under the new subsidy system, so that it is equally favorable as the old system. Finally, I add uncertainty to subsidy payments by assuming default probabilities in distributions over time.

3.1 The base case

The previous chapter constructs a cash flow and valuation model for wind energy investments, which this and the next chapter put to the test. A Monte Carlo simulation considers a single wind turbine.[27] I gradually define the model's input parameters to value the investment under a plethora of variations.

First, the production function in Equation (2) calls for a precise definition of a wind turbine. I assume it to have blade lengths l of 50 meters and an exposure to air density ρ of 1.28 kg/m^3. Moreover, it has a power coefficient C_p of 0.4, a maximum capacity of 3.5MW, a cut-in wind speed V_{min} of 3m/s and a cut-out speed V_{max} of 18m/s. The wind turbine operates 24 hours a day. The wind speed scale and shape parameters A and k are 9 and 2.5, respectively. Wind energy investors typically consider these wind speeds as favorable. Having defined the technical specifications of the investment opportunity and combining it with modeling wind speeds through a Weibull distribution and thereby utilizing the power function in Equation (2), I can draw randomized power estimates over time (MWh_t).

Secondly, and based on historical data from 2014 until 2017, I calculate the relevant parameters

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[27] I thank my supervisor Lars Christian Gaarn-Larsen from Energi30 for sharing his technical knowledge and data suggestions to specify a realistic numerical example for this paper.

to apply Equation (3) to forecast electricity prices over a time horizon of 25 years. First, I compute the seasonal parameters of Equation (4) through the least squared method, providing estimations for $s_1, ..., s_5$ and μ. Thereafter, the estimation removes the seasonality part from the log-normalized time series and uses the output to calibrate the stochastic part via a maximum likelihood estimation, providing estimates for α, κ, σ_X, σ_X, X_0, μ_J, σ_J, and λ_J. Utilizing these parameters allows me to run an electricity price simulation over any given time horizon. Because the valuation model forecasts income on a daily basis, dt equals $\frac{1}{365}$. Figure 3 exhibits a sample draw for the electricity spot price forecast. Even though I am only interested in a general price forecast over 25 years regardless of the actual investment's vintage, one could think of letting the simulation start in 2018 and running it until the end of 2042.

In accordance to the subsidy system until 20.02.2018, the subsidy parameters under the old system are $G = 33.5$€/MWh and $B = 3.1$€/MWh. The new tender-based system allows bids up to 13øre/kWh (17.4€/MWh) and distributes payouts over the first 20 years of the project. Though it is likely that the accepted bids are much lower than the maximum allowed,[28] I run this first simulation under S^{New} equal to 17.4€/MWh as a starting point. Under the base case, I do not assume uncertainty in subsidy distributions and apply Equation (9) and (10), or equivalent, apply Equation (11) and (16) with λ^{Old} and λ^{New} being 0. Subsequent simulations add uncertainty in future subsidy payouts, varying λ^{Old} and λ^{New}.

Average annual costs per year C_{yearly} are €72,000 or €197.26 a day, respectively. The Monte Carlo simulation predicts future daily incomes (I_t) over a time horizon of 25 years(or $T = 9125$ days), neglecting additional days in leap-years.

The choice of a reasonable risk-adjusted discount rate depicts a challenge. To start, the base case assumes r to be 7%. From discussions with institutional investors, this rate seems to qualify as an established threshold for investors to enter into energy infrastructure investments. A later sensitivity analysis varies this rate and examines an investment's exposure to the chosen rate.

The simulation runs 1000 times (N) under each of the two subsidy systems as well as under neither, drawing a total of 1000 present values. Finally, the ratio of the present value over capital expenditures (CAPEX) in $t = 0$ determines the investment's profitability. A ratio larger than 1 depicts a profitable investment opportunity, and vice versa. CAPEX equals €3.500.000 following a benchmark of €1.000.000 per MW.

The comparison of the distributions of $PV/CAPEX$ ratios under the old, new and no subsidy systems examines differences in the three regimes as well as their total value as part of the investment opportunity. Table 1 aggregates all assumptions for this base case scenario.

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[28] In fact, the first tender in the end of 2018 shows exactly that, see Appendix E. Average price premiums across all accepted bids is ca. 3.1€/MWh.

Table 1: Base case assumptions

This table provides estimates for a Monte Carlo simulation under the two different subsidy system as well as under no subsidies. *Panel A* provides estimates for the wind energy investment as requested by the power function in Equation (2). *Panel B* provides assumptions for the Weibull distribution's parameters, see Appendix B. *Panel C* documents electricity price forecast parameters for Equation (3). *Panel D* shows estimates for operational expenditures, specified under Equation (21). Finally, *Panel E* documents the remaining information needed for the analysis.

***Panel A**: Wind Turbine*

l	50	V_{min}	3
$A\ (= \pi l^2)$	7853.982	V_{max}	18
ρ	1.28	MW_{max}	3.5
C_p	0.4	h	24

***Panel B**: Wind Speeds*

A	9	k	2.5

***Panel C**: Electricity Price Forecast*

Stochastic Part		Deterministic Part	
α	-0.339	s_1	-0.012
κ	23.675	s_2	0.151
σ_X	1.058	s_3	-0.031
X_0	-0.121	s_4	-0.042
μ_J	0.002	s_5	3.198
σ_J	0.187	μ	0.024
λ_J	112.966		
dt	$\frac{1}{365}$		

***Panel D**: Subsidies*

Old System		New System	
G	33.5	S^{New}	17.4
B	3.1		

***Panel E**: Costs*

C_{Yearly}	72,000	C_{Daily}	197.26

***Panel F**: Other*

r	0.07	β	-0.045
$CAPEX$	3,500,000	T	9125
Δt	$\frac{1}{365}$	N	1000

3.2 Varying risk parameters

The base case scenario provides an attempt to value a wind energy investment opportunity as specified in Table 1. In another step, I vary three chosen risk parameters, determining their influence on the investment's risks and returns. The procedure goes as follows. I keep the assumptions of the base case scenario fixed and only adjust one of the three risk parameters at a time. For a single variation, I obtain a distribution similar to the base case, meaning that each data point in the varying range of the chosen parameter is used to simulate 1000 draws of $PV/CAPEX$. I obtain the mean and standard deviation and graphically illustrate their impact on the profitability ratio. Trends following the variation of these risk parameters reveal the investment's unique risk exposures.

First, I alter the wind speed scale parameter A under the Weibull distribution from 5 to 15m/s. The outcome of this sub-analysis is interesting as disparate geographical locations are subject to varying wind speeds. The results document the importance and dependence of environmental conditions for wind energy investment returns.

Secondly, the drift in the electricity price μ takes on values between -2 to 6%, allowing for differing expectations for long-run electricity price developments. As the electricity price constitutes one primary driver for the generated income of wind turbine investments, it is vital to acknowledge differences in the electricity price forecast. Investors have diverging expectations of price developments and can easily incorporate them into the valuation model. Moreover, it provides a threshold μ^* for which the investment becomes profitable.

Considering the importance and high impacts of discount rates in long-term investments, another series of simulations varies it from 0 to 12.5%. The simulations' outcomes provide an approximation under which discount rates the investment opportunity remains profitable. This analysis is interesting as investors have heterogeneous requirements with regards to the risk-adjusted discount rate. They may quantify the inherent risks of energy infrastructure investments in a very different way.

3.3 The equilibrium bid

Next to a variation in three chosen risk parameters, I compute an equilibrium bid under which the old subsidy systems is just as favorable as the new one. In essence, I vary the subsidy bid in S^{New} from 0 to 25€/MWh. For each of the data points in the range given for S^{New}, the simulation runs 1000 times and then averages over $PV/CAPEX$. The point where the mean in the outcomes of $PV/CAPEX$ under the old subsidy system is equivalent to the mean of $PV/CAPEX$ under the new system is where the two regimes are equally favorable. Under that particular bid, investors would be indifferent under which one they operate.

All other assumptions remain constant as exhibited in Table 1. If other assumption would change, the outcome of the equilibrium bid would also change, so that the results only apply to this specific numerical example. Also, one should keep in mind that the maximum bid is capped at 17.4€/MWh, so that bids greater than that are not feasible in reality and are only used in this simulation.

3.4 Uncertainty in subsidies

Finally, I add uncertainty to future subsidy distributions, see Figure 6 for an example. Specifically, I vary the likelihood of subsidy cuts through λ^{New} and λ^{Old} and incorporate uncertainty in future distributions according to Equations (11)-(20). Here, λ^{New} and λ^{Old} document yearly subsidy cut probabilities.

Table 2 provides the numerical assumptions for the likelihood and magnitude of subsidy cuts. As in the previous cases, I run an individual simulations for single data points within the ranges of λ^{New} and λ^{Old}. For every single variation I obtain a distribution of outcomes for each of the subsidy models as well as the subsidy-free case.

Table 2: Assumptions under uncertainty in subsidies

This table provides additional information needed for the analysis of subsidies under uncertainty. Other numerical estimates from Table 1 remain unchanged. The parameters λ^{Old} and λ^{New} are varied within the range of 0 until 0.5 and are expressed in yearly terms. The simulation applies these estimates as defined by Equations (11)-(20).

Old System		New System	
G_0	33.5	S_0^{New}	17.4
λ^{Old}	0 - 0.5	λ^{New}	0 - 0.5
u_0	5	q_0	2.5
u_1	3	q_1	2
B	3.1		

The assumption for subsidy cuts are arbitrary, in particular for u_0, u_1, q_0 and q_1. The reason for u_0 and u_1 being lower in absolute value than q_0 and q_1 is that the starting point under the old subsidy scheme is much higher than under the new subsidy system. The purpose of this simulation is to investigate the investment's risk and return dynamics under increases in the probability of future subsidy cuts. The findings provide an attempt of quantifying the value of subsidies in the renewable energy industry and help answering the question how investors are affected by default probabilities in subsidy distributions.

4 Results

I provide findings for the valuation model under the new, old and no subsidy scheme and according to the different specifications outlined in the previous chapter. I focus on the changing expectations of $PV/CAPEX$ as an indication for risk exposure. This includes the development of mean values in the distributions of simulations as well as their volatility. The higher (lower) the mean, the more (less) profitable the investment opportunity. The higher the volatility, the more uncertain the outcome, implying lower risk-adjusted returns, and vice versa.

The remainder of this chapter is structured as follows. First, I report the results of the base case scenario. Second, I examine the behavior of $PV/CAPEX$ under variations in the three risk parameters of wind speeds, electricity price forecasts and discount rates. Third, I evaluate the outcome under different subsidy bids in the new subsidy scheme to determine an equilibrium bid under which the two subsidy schemes are equally favorable. Fourth, I evaluate the model under uncertainty of subsidy distributions over time. Finally, I apply another type of subsidy model (variable premium) and compare it to the old and new subsidy models, i.e. fixed premium systems.

4.1 The base case

The base case scenario runs a Monte Carlo simulation under the numerical assumptions in Table 1, and separately for the new, old and no subsidy system. Figure 7 reports the findings.

The distributions of all three simulations are close to normal distributions.[29] The standard deviation of the distributions is low in relative terms. Under the current base case scenario, the project's outcome can be predicted with a moderate degree of certainty.

A ratio of $PV/CAPEX$ greater than one indicates that the investment is favorable as the initial investment costs are lower than the present value of discounted cash flows. This is the case under all scenarios. However, looking at the case of no subsidies, the investment turns out to be barely profitable as its mean value is just above the threshold. Keeping in mind that the base case values the investment under the assumption of a discount rate of 7% as well as yearly increase in electricity prices of 2%, it seems unlikely that many investors would pick up on the investment opportunity without the guarantee of additional subsidies.

Looking at the two considered subsidy schemes in wind energy, they both seem to be very

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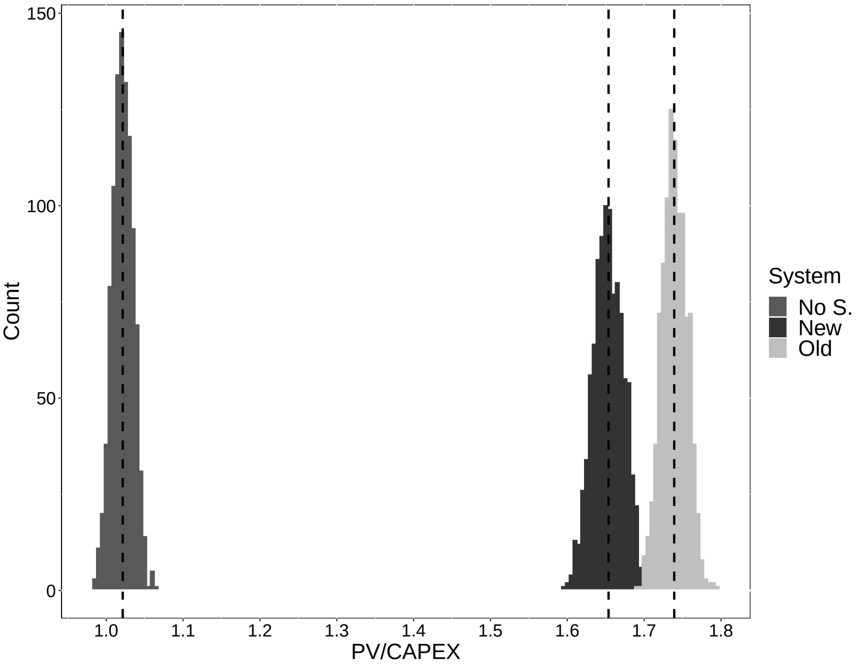
[29] A Shapiro-Wilk test fails to reject at any significant level. Appendix D further exhibits quintile-quintile plots showing strong support of the normal distribution.

Figure 7: Distribution of income simulation in the base case

The figure exhibits three histograms each drawing from 1000 outcomes of $PV/CAPEX$ based on assumptions of Table 1 and under the old, new and subsidy-free (No S.) systems. Under the old subsidy system investors are compensated with 25øre/kWh (€33.5/MWh) for the first 22.000 full load hours on top of 2.3øre/kWh (€3.1/MWh) balancing costs for electricity over the lifetime of a project. Under the new subsidy system, investors are compensated with €17.4/MWh, which is the maximum bid under the compensation system. Assuming no subsidies, investors receive no additional compensation apart from the market price to which they sell their electricity.



favorable. The present value of discounted cash flows manifests about 65-75% above the initial investment costs. It comes as no surprise that, under the old subsidy scheme, we have seen a sharp increase in total capacity development over the previous decades, see Figure A.1 in Appendix A.

The two subsidy compensation systems yield not far apart from each other. The old subsidy compensation system ranks a little higher than the new scheme. The new subsidy system is run under the assumption of the maximum bid allowed, which is unrealistic to occur in the tendering process, see Appendix E. Considering that the subsidy-free scenario is profitable in itself, the possibility of seeing low bids in the future is likely. This will diminish parts of the investment's value, however, considering a margin of about 70% under the maximum bid, they will stay profitable for bids much lower. Creating competition through budget constraints and across technologies, meaning that only the lowest bids are accepted until the budget for a single tender runs out, will force investors to place lower bids, in this case S^{New}, and give up some of their investment's return. By definition, it is better for investors to give up some (large) parts of the subsidy value instead of not being granted any additional compensation at all by bidding too high. Considering that low bids will likely occur at future auctions indicates that the old subsidy compensation scheme was much more profitable in comparison to the new tender-based system.

As mentioned before, the comparison of the two subsidy systems to the case of no subsidies in Figure 7 illustrates that subsidies make up a large share of the total investment. This conclusion strengthens the hypothesis that renewable energy investments in Denmark are still dependent on additional subsidy compensation and are not yet in a position, where they can compete with subsidy-free conventional energy sources. On the other hand, considering the present value of subsidies of more than 2/3 of the total investment costs, also empowers the previous finding that investors can afford to give up parts of that share by placing low bids at the annual auctions. It therefore seems unlikely that bids close to the maximum bid of €17.4/MWh will occur in any of the future tenders.

4.2 Varying risk parameters

The second simulation exercise varies the base case scenario in a number of uncertainty parameters. All other assumptions as defined in Table 1 stay fixed, while only one variable at a time changes. I vary the scale parameter in wind speeds, the drift in the long run projection of electricity prices, and the discount rate applied to future cash flows. Figure 8 displays the results under the old, new and subsidy-free (*No S.*) systems.

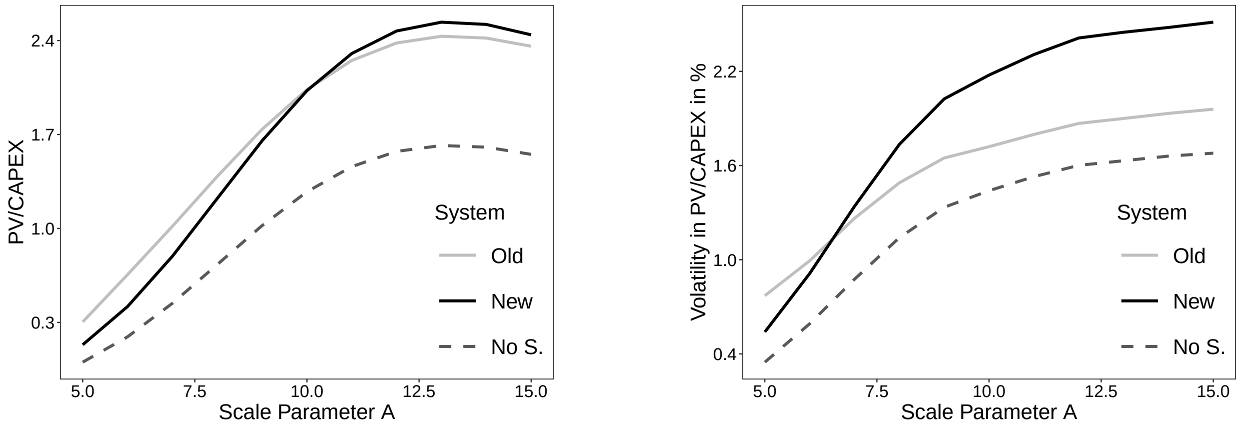
Figures 8a and 8b document a changing wind speed scale parameter A in relation to the investment's valuation. This is important to consider, because different geographical locations are exposed to different environmental conditions, including wind speeds.

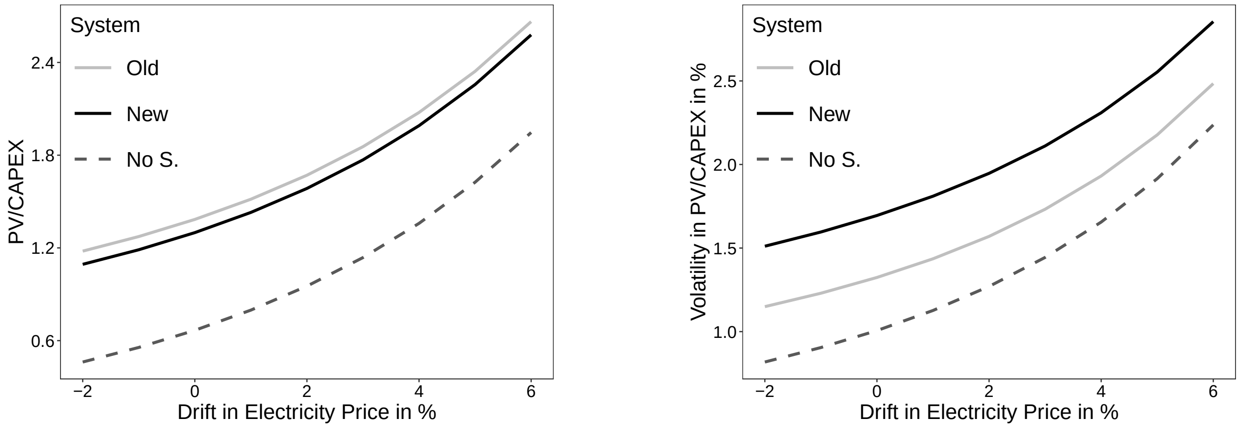
The first observation is that higher wind speeds increase returns, see Figure 8a. The valuation sharply increases under all subsidy schemes from 5m/s up until about 10m/s. The breakthrough to profitability comes at around A =7-7.5m/s considering the old and new subsidy scheme. The subsidy-free based system becomes profitable at around A =8.5m/s. Though with less intensity, the slope keeps increasing after 10m/s until a maximum level of about 13m/s and then slowly decreases again. This decrease is due to the fact that the wind turbine, in this example, has a cut-off level V_{max} of 18m/s. The higher the scale parameter A, the more days occur under which the turbine is turned off because of wind speeds exceeding V_{max}, leading to neither energy output nor income. Moreover, the volatility in draws of $PV/CAPEX$ increase with an increase in the scale parameter A. This comes as no surprise as a higher scale parameter indicates a higher volatility in the daily wind speed averages, see Figure B. In a nutshell, the environmental conditions with regards to wind speeds are a vital factor for returns in wind energy investments.

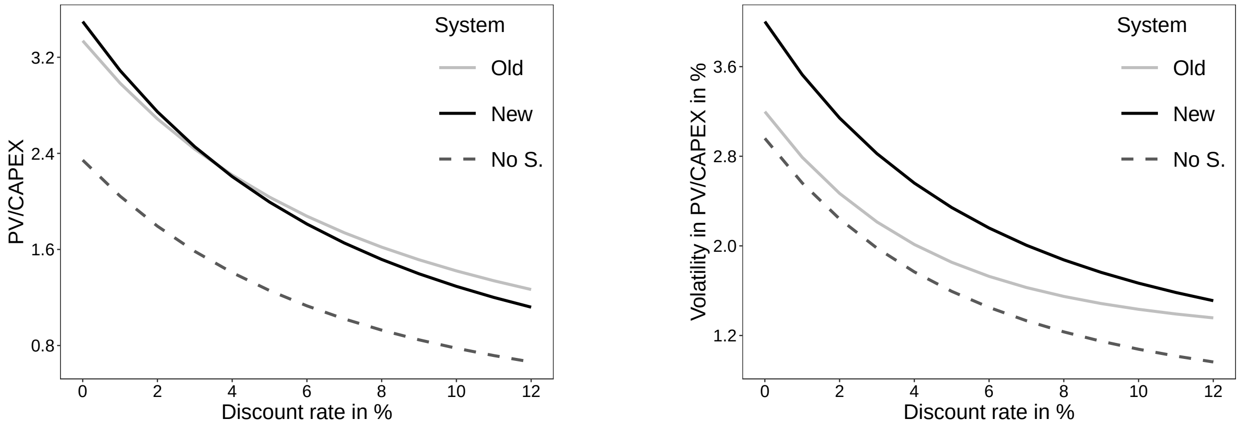
Furthermore, it is interesting to see that the old and new subsidy systems cross at a given

Figure 8: Varying risk parameters

These figures show the results of variations in single uncertainty parameters while keeping all other assumption from the base case in Table 1 fixed. Each data point in the graphs represents the mean of $PV/CAPEX$ over 1000 draws. In particular, the figures represent variations in wind speeds, electricity price drifts, and discount rates.


(a) Changing wind speeds **(b)** Wind speeds and volatility


(c) Drift in electricity prices **(d)** Electricity prices and volatility


(e) Changing discount rates **(f)** Discount rates and volatility

scale parameter of approximately 10m/s, see Figure 8a. Also, at higher productivity levels, the new system increases more in profitability than the old system. This is due to the fact that the new subsidy system is not bound by total production, but instead by time, so that higher productivity is promoted to a larger extent. The new system thereby encourages investors to build more productive wind turbines to best exploit the new subsidy system.

Finally, the higher the scale paramater A is, the higher the volatility in the distribution becomes, see Figure 8b. A higher scale parameter comes with increasing volatility in cash flows over time, which, by default, leads to higher volatility in present values.

Figure 8c and 8d show a sensitivity analysis with regards to varying expectations in long-term developments of electricity prices as denoted by μ. As expected, an increase in μ yields a monotonically increasing ratio of $PV/CAPEX$. The electricity price depicts, next only to subsidies, the only source of income. A high electricity price yields a high income, and vice versa. The project's value is highly dependent on the outlook of the electricity price, see Figure 8c. An outlook of a yearly increase in the electricity price of about 4% annually leads to a present value of future cash flows of more than twice the initial investment costs under this simulation.

The old and new subsidy scheme stay profitable even under the consideration of a drift μ of -2%. Subsidy-free investments, however, cannot allow any negative drift in future electricity prices, which might be one reason investors to barely engage in wind energy without additional compensation. The fear of negative or very low future growth rates in electricity prices will make these investments unprofitable immediately. The volatility of present values of future cash flows also increases along with surges in drifts. This is reasonable as cash flows deviate further from the average mean over time with rising electricity prices.

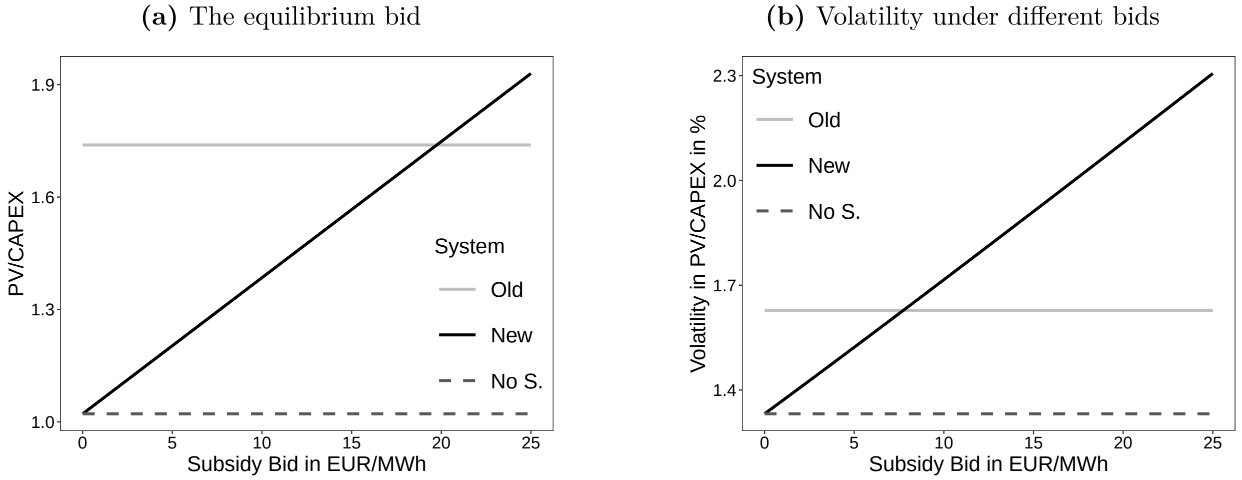
Finally, Figures 8e and 8f document how the valuation of wind energy projects relies on discount rates. Wind energy investments are long-term and the chosen time-horizon for this numerical application is 25 years, making the investment, by nature, highly dependent on discount rates. Even small incremental changes in the assumption of the discount rate yield significant changes in the investment's valuation. In this example, investors with a required return of more than ca. 8.5% will find themselves in a position, where they would choose not to invest under the subsidy-free system. Interestingly, the old and new subsidy schemes cross at a discount rate of a little over 3%. The new subsidy scheme yields higher income at later points in the project's life-time because of the comparatively long eligibility of 20 years. The old subsidy scheme, however, only grants subsidies for the first 22.000 full-load hours. These first 22.000 full-load hours are typically exhausted after the first 5-7 years. This means that cash flows are higher in the beginning of the project in comparison to the new subsidy scheme as the old scheme grants 33.5€/MWh relative to a maximum of 17.4€/MWh. If the discount rate rises, cash flows in the distant future are discounted more heavily in comparison to cash flows in the near future, which is why the new system is more profitable for very low rates.

4.3 The equilibrium bid

The old and the new subsidy scheme differ in their construction. While the old system comes with a fixed top-up of 33.5€/MWh to the electricity price for the first 22.000 full-load hours, the new system organizes yearly auctions, where investors place bids for additional compensation per MWh they wish to receive for a time horizon of 20 years. In this section, I keep the assumptions of Table 1 fixed except for varying the parameter of S^{New}, and thereby run the new subsidy scheme under different bids. I run the analysis for changing bids in S^{New} from 0 to 25€/MWh despite the fact that, in the real world, S^{New} is capped at 17.4€/MWh. Figure 9 shows the results.

Figure 9: Changing subsidy bids

Figures 9a and 9b show the results for a variation in the single parameter of S^{new} while keeping all other assumption from the base in Table 1 fixed. Each data point in the graphs represents the mean value of $PV/CAPEX$ over 1000 draws. As the old and subsidy-free systems are not affected by differences in the bids of S^{new}, they remain constant.


(a) The equilibrium bid

(b) Volatility under different bids

Both the old and the subsidy-free system remain unaffected to the bids in the new subsidy compensation scheme as they are unrelated to S^{New}. The new subsidy compensation increases monotonically linear to the level of the bid. The more the subsidy payout increases with a higher S^{New}, the more profitable the investment becomes. Cash flows rise and so does the present value of the sum of cash flows.

I find an equilibrium of the new and old subsidy scheme at $S^{New} \approx 20$€/MWh, which is above the maximum bid allowed. Everything below 20€/MWh yields lower present values than under the old subsidy scheme, so that investors will almost certainly be worse off (given the assumptions in Table 1). At $S^{New} = 0$€/MWh, the assumptions are a reflection of the subsidy-free scenario and therefore the simulation yields the same outcome.

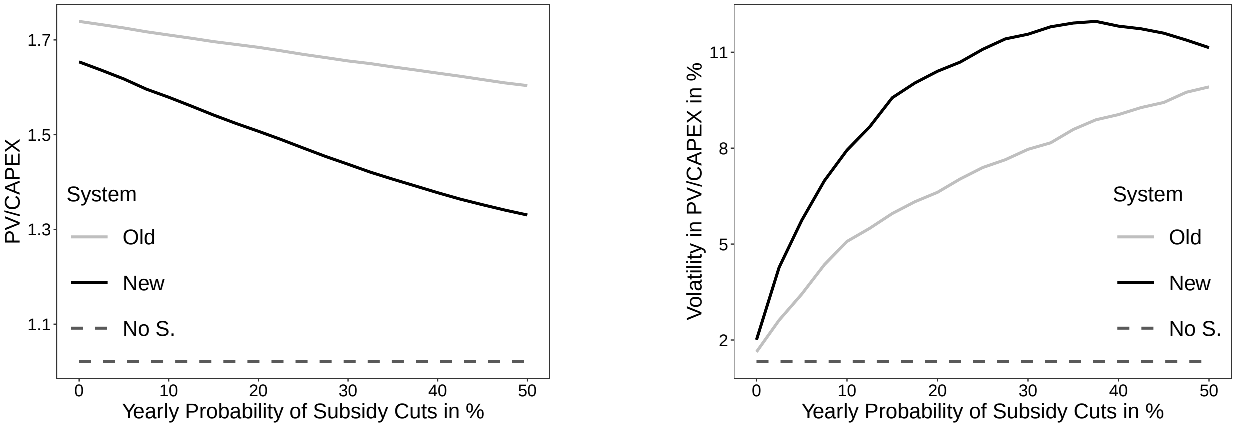
Interestingly, volatility increases with higher degrees of S^{New}. However, this finding is reasonable as higher subsidy compensation must also lead to increased volatility throughout the entire project due to the final five years of the project being subsidy-free. The average differences between cash flows of the first 20 years and the last five years, which are subsidy-free in any case, rises with a higher S^{New}.

4.4 Uncertainty in subsidies

Finally, I consider uncertainty in subsidy compensation over time according to Equations (11)-(20). The assumption of the base case scenario in Panel D of Table 1 are exchanged by Table 2. The parameters of λ^{Old} and λ^{New} depict yearly probabilities of subsidy cuts, which the simulation varies between 0 and 50%. Figure 10 shows the results.

Figure 10: Uncertainty in subsidies

Figures 10a and 10b exhibit uncertainty in the subsidy compensation by S^{Old} and S^{New}. The assumptions from the base case scenario in Table 1 Panel D are partly redefined by Table 2. The simulation varies λ^{Old} and λ^{New}, which express the default probability. Each data point in the graphs represents the mean or standard deviation of $PV/CAPEX$ over 1000 draws, respectively. As the subsidy-free system (No S.) is not eligible for subsidies, it is not affected by default probabilities in subsidy cuts.



(a) Uncertainty in subsidies

(b) Subsidy defaults and volatility

The two subsidy schemes, old and new, react negatively to an increase in the probability of subsidy cuts. It comes as no surprise that the higher the probability, the less valuable the investment opportunity becomes. What is worthwhile noting, however, is that the new subsidy compensation system reacts more negatively to surging default probabilities. The explanation behind this observation is that the new subsidy system distributes payouts over a much longer time horizon and is therefore exposed to the risk of subsidy cuts over a longer time too. Under no circumstance is the new subsidy system more profitable than the old one. By nature, the subsidy-free system does not react to subsidy default probabilities as it does not receive any type of additional compensation in the first place.

The volatility in the draws of $PV/CAPEX$ increases according to the default probability in subsidy distributions over time under both the old and new system up until around $\{\lambda^{Old}, \lambda^{New}\} \approx 35\%$. An increase in the probability of subsidy cuts leads to differences in subsidy compensations over time and therefore increases the volatility in cash flows. This effect is higher under the new system, which, again, is due to its longer exposure to subsidy cuts. Beyond 35% in the yearly default probability, the new system decreases again in volatility. A higher default probability in λ^{New} leads to significant subsidy cuts early in the project lifetime and therefore reduces risk as measured by the distribution of cash flows over time.

4.5 Applying an alternative subsidy scheme

Section 2.3 elaborates on the two main types of subsidy structures. The subsidy structures investigated in this paper each identify as a fixed premium system, constrained either by time or production hours. The other main type of premium system refers to as variable, see Figure 4b. Effectively, the producer is guaranteed a minimum electricity price floor when producing and selling power. This guarantee serves as a put option to the producer, where the price floor can be considered the strike price.[30]

This section reviews that alternating specification of a subsidy scheme and compares a hypothetical price floor of 40€/MWh for a ten-year period to the old, new and no subsidy case. This means that investors receive at least 40€/MWh for a period of ten years for every production unit. When market prices are higher, they receive the market price and no additional compensation. After a period of ten years, investors only receive the current market price of electricity.[31] Figure 11 shows results for varying electricity price expectations (Figure 11a and 11b) and strike prices (Figure 11c and 11d).

The results show that the variable subsidy scheme participates less on increasing drifts in electricity prices, see Figure 11a and 11b. That is, higher growth rates in electricity prices mean higher returns for wind energy projects subject to a variable subsidy scheme too, but to a lesser

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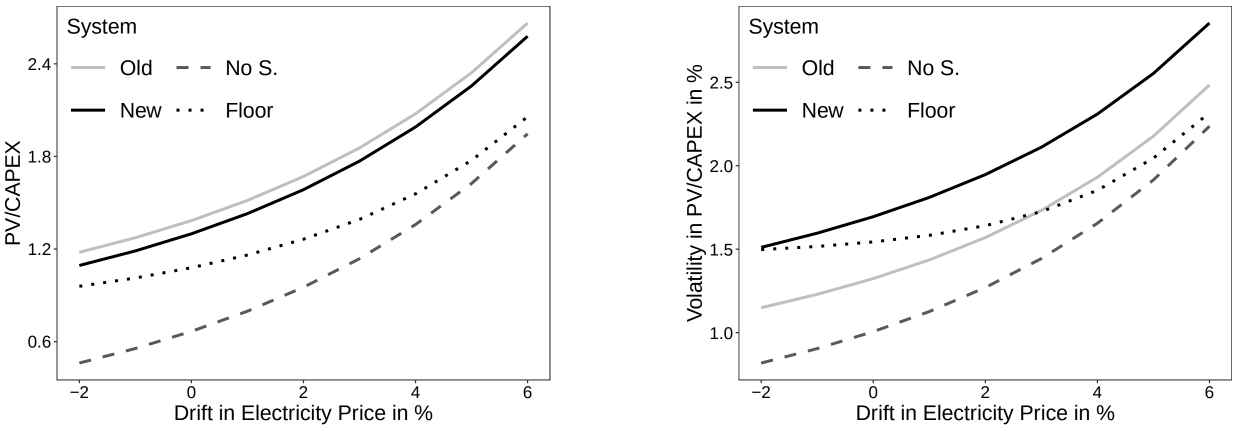
[30] For example, the UK has implemented such a scheme. They refer to it as a Contract for Difference (CfD) agreement, see at GOV.UK. Also, Denmark discusses such a scheme to be implemented for future energy projects, see Danish Ministry of Climate, Energy and Utilities.

[31] This specification is chosen arbitrarily, but could well reflect an actual policy proposal.

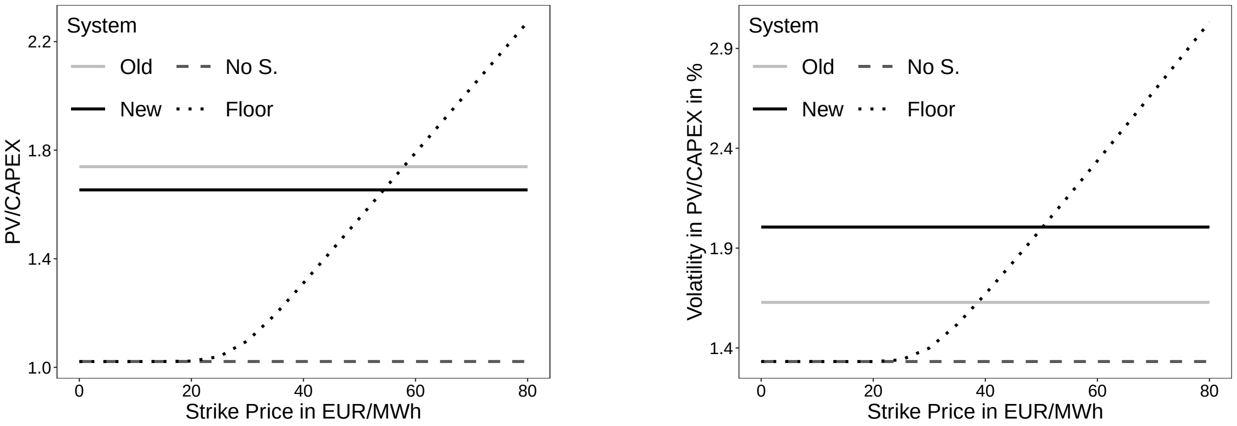
Figure 11: Varying risk parameters and the variable premium

The figures exhibit the outcome of a variation in a single uncertainty parameter while keeping all other assumption from the base case in Table 1 fixed. Additionally, I apply a variable subsidy scheme (denoted as *Floor*), which guarantees a minimum of 40€/MWh for a ten-year period if current power prices are below that level. Each data point in the graphs represents the mean value of $PV/CAPEX$ over 1000 draws. In particular, the figures represent variations in electricity price drifts and strike prices.

(a) Drift in electricity prices **(b)** Electricity prices and volatility



(c) Varying strike prices **(d)** Volatility under varying strike prices



extent than for the fixed premium system (old and new subsidy scheme). This is reasonable as higher growth rates in electricity prices imply that investors participate less and less from additional subsidy contributions as prices increasingly trump the guaranteed price floor.

On the other hand, the fixed premium subsidy scheme pays out subsidies regardless of electricity price levels. The figure shows that the lower bound of electricity prices, provided through the minimum compensation of 40€/MWh, provides a hedge to investors that is valuable from a risk and return perspective. The positive effect of this hedge materializes when considering negative drifts, in which case returns converge under all subsidy systems. Depending on the level of the price floor, this hedge could have the power to put investors in a superior position when securing financing for new projects.

Figure 11c and 11d underline that returns of a variable premium project are largely subject to the strike price that is set by policy makers. Low strike prices lead to a situation in which premia are rarely paid, because electricity prices almost always exceed the strike price. Only after a minimum price floor returns monotonically increase. In this simulation, a strike price of ca. 54€/MWh would yield the same total returns as the new subsidy system under the maximum bid would earn. A strike price of ca. 58€/MWh would expose an investor to the same total discounted cash flows as the old subsidy system.

I run this analysis for varying discount rates, wind speed expectations and uncertainty in subsidy contributions also, see Figures F.1, F.2 and F.3 in Appendix F. Trends for the variable premium system are similar to the old, new and no subsidy case. The variable premium system shows to be less affected by increases in subsidy cut probabilities (with respect to cuts in the strike price level). There are two reasons for that. First, this analysis assumes a pay-out period of 10 years, which is significantly less in comparison to the new subsidy system. Second, total contributions under a strike price of 40€/MWh are not as high as under the old and new subsidy system when assuming the maximum bid. Subsidy cuts therefore have less of an impact if total contributions as a share of total cash flows are lower to begin with.

This exercise is relevant not only to investors but also for policy makers or stakeholders as banks or other financiers. It documents opportunities and drawbacks between two inherently different types of subsidy structures. Also, it shows that the proposed model to value subsidies provides the possibility to easily compare subsidy schemes of very different kinds.

5 Conclusion

This paper introduces a general income and valuation model for wind energy projects with focus on the Danish market. It takes into account the novel production function of wind turbines, a forecast model of electricity price developments as well as different subsidy schemes. The model allows to value investment opportunities in wind energy with the opportunity to vary individual and distinct parameters that matter for this asset class and its risk exposure evaluation.

Putting the model to the test in a Monte Carlo simulation yield four main findings. First, long-term electricity price developments and wind speeds are major drivers for the risk and return performance of investment opportunities. Second, Denmark's new subsidy compensation system, on average, is less profitable as the old subsidy system from an investor's perspective. This is due to a competitive tender-structure with technology neutrality and longer distribution periods. Low bids and therefore low subsidies in the future are likely. Fourth and finally, uncertainty in subsidy distributions over time has significant effects on the decision-making process of investors. If investors find future subsidy distributions to be uncertain, it significantly impacts asset valuations. This information is important not only for investors but also for policy makers to consider when aiming to incentivize private capital to flow into this asset class.

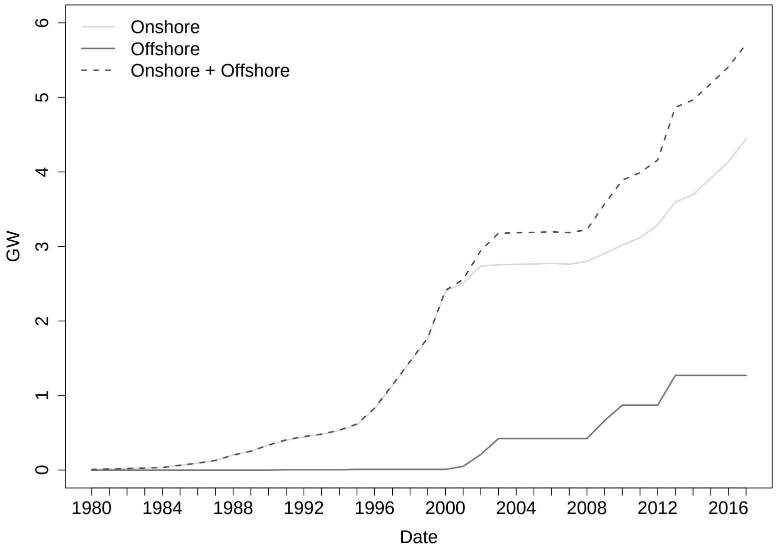
Finally, this model allows to adjust for alternating specifications of subsidy schemes. An arbitrary numerical application to value a variable premium system in comparison to existing subsidy structures shows that variable premiums provide a hedge to investors against long-term decreasing power prices but, on the other hand, lets them participate less from increasing prices. Also, price floors materialize only at significantly high levels.

Appendices

A The Wind Energy Market in Denmark

In this appendix section I show information on wind energy capacity in Denmark. The data suggests that wind energy continues to strengthen its position in the total capacity mix.

Figure A.1: Capacity development in Denmark from 1980 until 2016



Source: Bloomberg New Energy Finance (BNEF)

B The Weibull Distribution

Consisting of two parameters, the Weibull probability density function $f(v)$ applied to the average wind v is

$$f(v) = \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} \exp\left(-\left(\frac{v}{A}\right)^{k}\right), \tag{B.1}$$

in which A and k depict the scale and shape parameter, respectively. The average wind speed $E(V)$ and the variance $Var(V)$ are defined as

$$E(V) = A\Gamma\left(1+\frac{1}{k}\right) \tag{B.2}$$

$$Var(V) = A^2\left(\Gamma\left(1+\frac{2}{k}\right)^2\right), \tag{B.3}$$

where Γ exhibits the Gamma function (Yu and Tuzuner, 2008). To model average daily wind speeds of V_t, I use this Weibull distribution through an educated guess of k and A. Figure B.1 graphically illustrates the Weibull distribution with a scale and shape parameter of 9 and 2.5, respectively.

Figure B.1: The Weibull distribution

This Weibull distribution is assumed throughout the simulation of future income with a scale parameter of $A = 9$ and a shape parameter of $k = 2.5$.

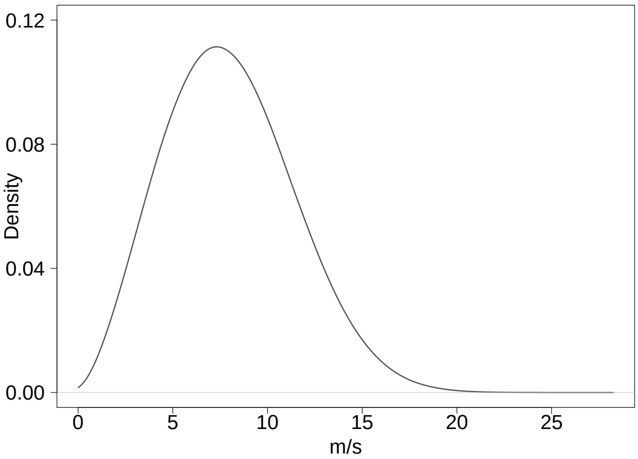
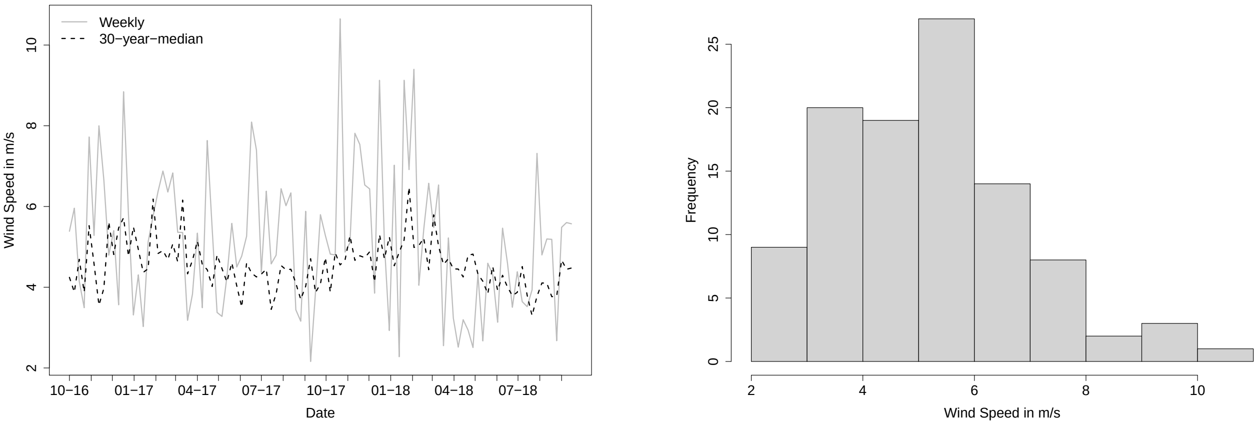


Figure B.2 presents data on average wind Speeds in Denmark.

Figure B.2: Wind speeds in Denmark

Figure B.2a shows weekly and 30-year-median wind speeds in m/s over time. Figure B.2b documents the distribution of weekly median wind speeds in Denmark, measured in m/s. *Source:* Bloomberg New Energy Finance (BNEF).



(a) Wind speeds over time

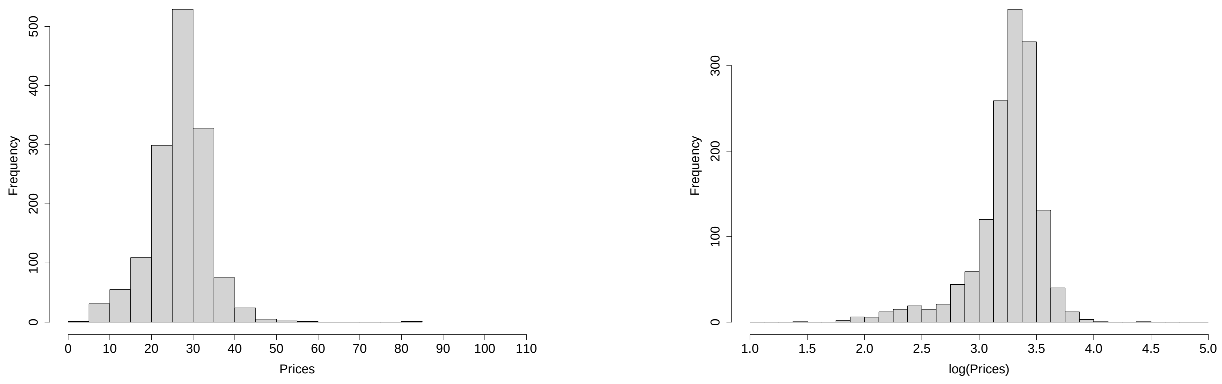
(b) Wind speed distribution

C Electricity Price Forecasts and the Impact of Production

I provide more information on both historical and simulated electricity prices in Figure C.1. Furthermore, I document additional analysis on the relationship between electricity prices and power production in Table C.1 and Figure C.2.

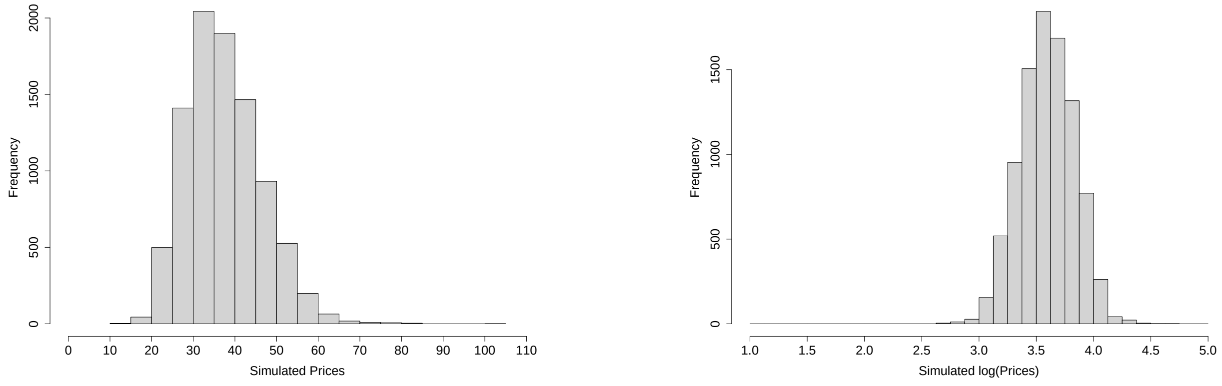
Figure C.1: Electricity price distributions

The distributions in subfigures C.1a and C.1b depict the actual daily average spot price and log(price) of the Nordic electricity market irrespective of capacity congestion in the individual interconnections between the areas of Denmark, Sweden and Germany (referred to as SYSTEM) as obtained from Energi Data Service. Figures C.1c and C.1d show the simulated price and log(price) distributions under the model.



(a) Price distribution

(b) Log-price distribution



(c) Simulated price distribution

(d) Simulated log-price distribution

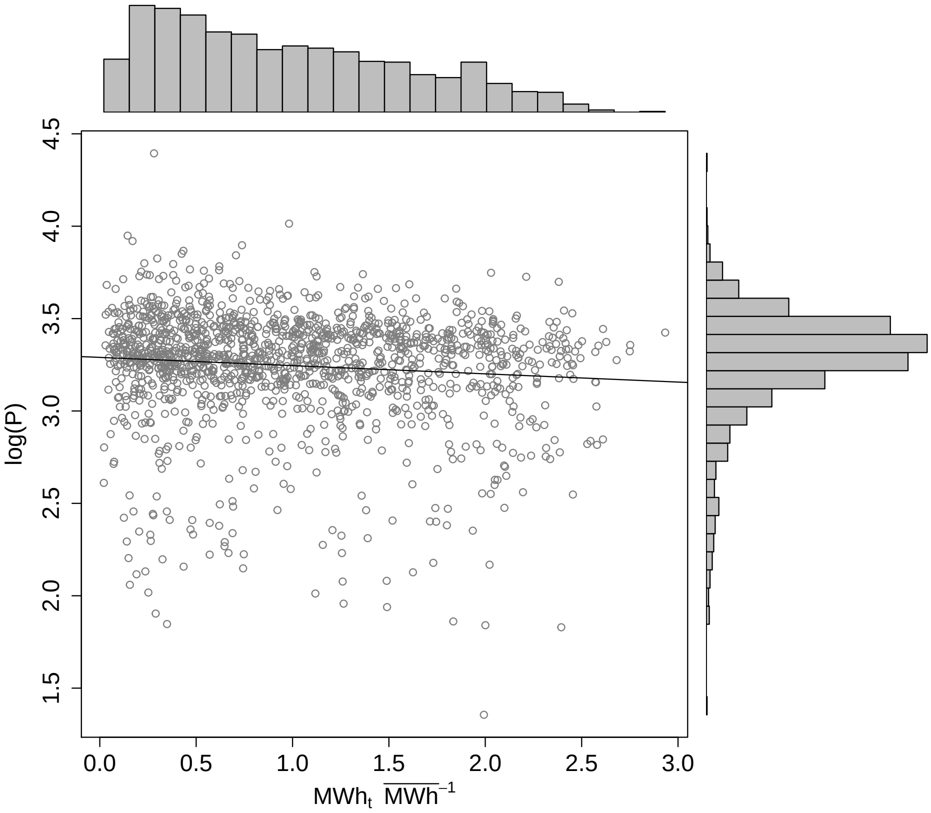
Table C.1: The impact of production

This table documents the results of regressions of daily electricity log-prices from 2015 until 2017 against production. Production_t is measured by the ratio of daily production at time t over the average of the time series. The numbers in parenthesis exhibit standard errors while the stars denote significance levels. Data Source: Nord Pool AS.

	Dependent variable:		
	$\log(P_t)$		
	(1)	(2)	(3)
Production_t	-0.045^{***}	-0.044^{***}	-0.045^{***}
	(0.012)	(0.005)	(0.005)
$\log(P_{t-1})$		0.921^{***}	0.877^{***}
		(0.010)	(0.026)
$\log(P_{t-2})$			0.048^{*}
			(0.026)
Constant	3.290^{***}	0.299^{***}	0.288^{***}
	(0.014)	(0.032)	(0.033)
Observations	1,461	1,460	1,459
Adjusted R^2	0.009	0.858	0.858
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Figure C.2: Prices and production

The graph plots log-prices of the daily electricity spot price against production. The red line (regression of log-prices against the daily production ratio over its mean), indicates a minor but yet significant negative causality, see Table C.1. Data Source: Nord Pool AS.

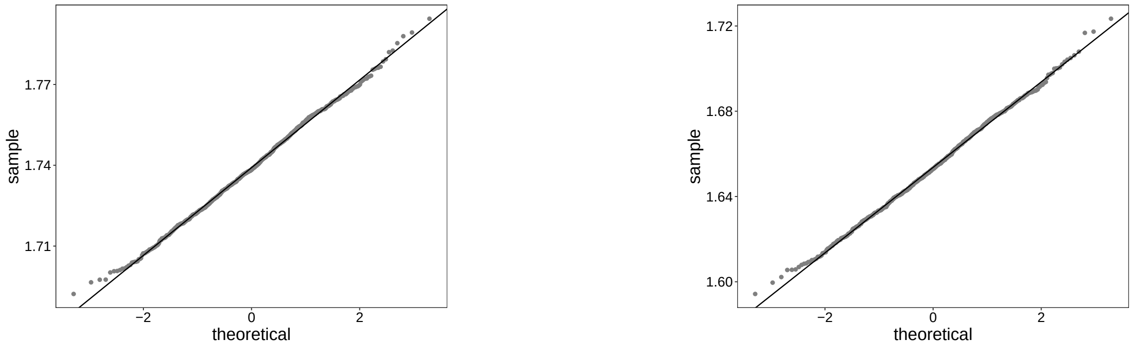


D The Base Case Simulation

In this appendix section I provide analyses on the resulting distributions under the base case simulations as shown in Figure 7. Specifically, I compare the simulation output relative to that of a normal distribution.

Figure D.1: Quantile-quantile plots

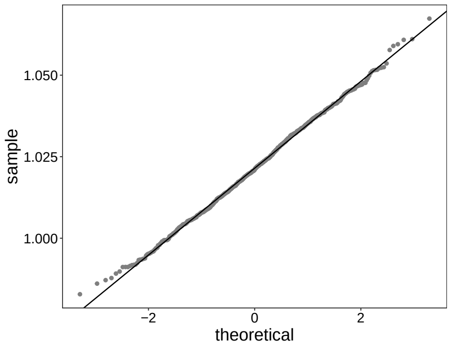
Figures D.1a, D.1b and D.1c each show the deviation of 1000 outcomes of $PV/CAPEX$, based on Figure 7, within the old, new and subsidy-free systems and under the base case scenario of Table 1 from the normal distribution (black line). Under the old subsidy system, investors are compensated with 25øre/kWh (33.5€/MWh) for the first 22.000 full load hours on top of 2.3øre/kWh (3.1€/MWh) balancing costs for electricity over the lifetime of a project. Under the new tender-based subsidy system, investors are compensated with up to 17.4€/MWh, which serves as the assumption in the model. Under the subsidy-free system, investors receive no additional compensation apart from the market price to which they sell their electricity.



(a) The old subsidy system

(b) The new subsidy system

(c) Subsidy-free system



E The first Tender 2018

I show the accepted bids under the first technology-neutral tender, referred to as the new subsidy scheme. Accepted bids are significantly lower than the maximal bid allowed, see Table E.1.

Table E.1: The first technology-neutral tender under the new subsidy system from 2018

The Danish Energy Agency held their first technology-neutral tender for subsidies from September 27, 2018 until November 26, 2018. The budget amounted to 254 mDKK and a total of 17 bids across ca. 260MW onshore wind and ca. 280MW solar PV were placed. The accepted bids include total project capacities of ca. 165MW onshore wind and ca. 101MW solar PV. This total capacity covers the electricity consumption of around 160,000 Danish households. The winning bid's value-weighted premium is 2.28øre/kWh or ca. 0.31Eurocent/kWh. Source: Energistyrelsen, Fact sheet on the result of the technology neutral tender 2018.

Winners	Technology	Offered price premium (øre/kWh)	Capacity (MW)	Share of budget	Municipality
1. NRGi Wind V A/S	Wind	1.89	28.8	11.9	Thisted
2. K/S Thorup-Sletten	Wind	1.98	77.4	33.5	Jammerbugt and Vesthimmerland
3. SE Blue Renewables DK P/S	Wind	2.50	59.3	32.4	Randers
4. Solar Park Rødby Fjord ApS	Solar	2.84	60.0	12.7	Lolland
5. Solar Park Næssundvej ApS	Solar	2.84	30.0	6.3	Morsø
6. Better Energy Frederikslund Estate ApS	Solar	2.98	11.5	3.1	Slagelse

F An alternative Subsidy Scheme

In this appendix section I document additional simulation results under the variable premium system. The price floor in this simulation is 40€/MWh, which the investor receives for a period of ten years.

Figure F.1: Discount rates and the variable premium

Figures F.1a and F.1b show the outcome of the variation in discount rates for different subsidy schemes while keeping all other assumption from the base case in Table 1 fixed. Each data point in the graphs represents the mean or standard deviation of $PV/CAPEX$ over 1000 draws. Next to the old, new and no subsidy case, I apply a variable subsidy scheme (denoted as *Floor*), which guarantees a minimum of 40€/MWh for a ten-year period if power prices are below.

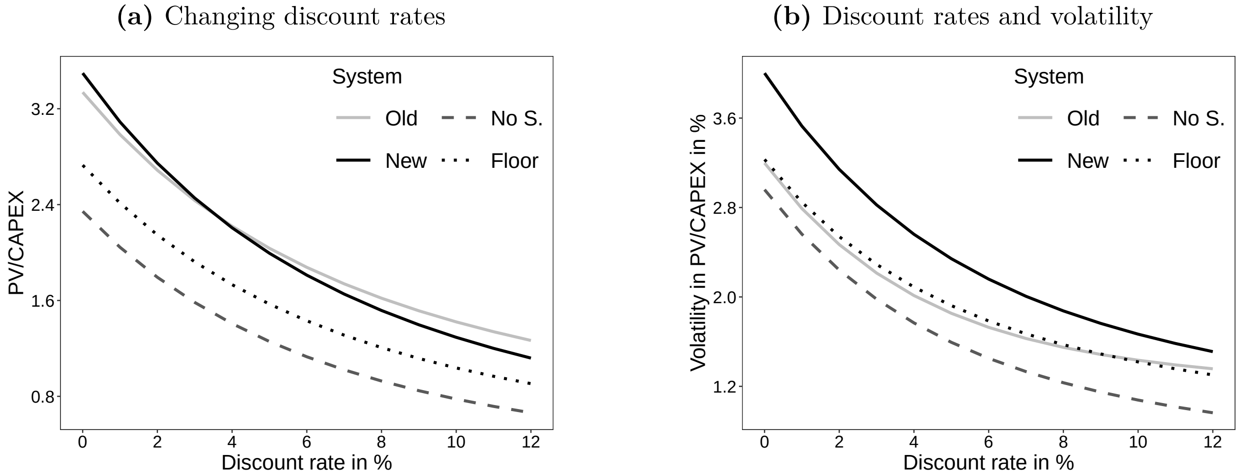
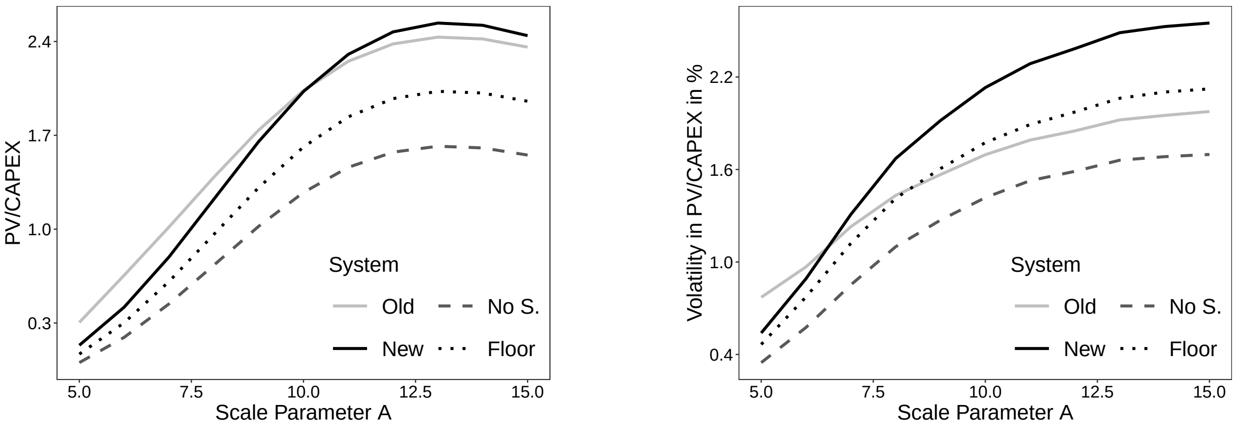

(a) Changing discount rates **(b)** Discount rates and volatility

Figure F.2: Wind volatility and the variable premium

Figures F.2a and F.2b show the outcome of the variation in wind speeds for different subsidy schemes while keeping all other assumption from the base case in Table 1 fixed. Each data point in the graphs represents the mean or standard deviation of $PV/CAPEX$ over 1000 draws. Next to the old, new and no subsidy case, I apply a variable subsidy scheme (denoted as *Floor*), which guarantees a minimum of 40€/MWh for a ten-year period if power prices are below.

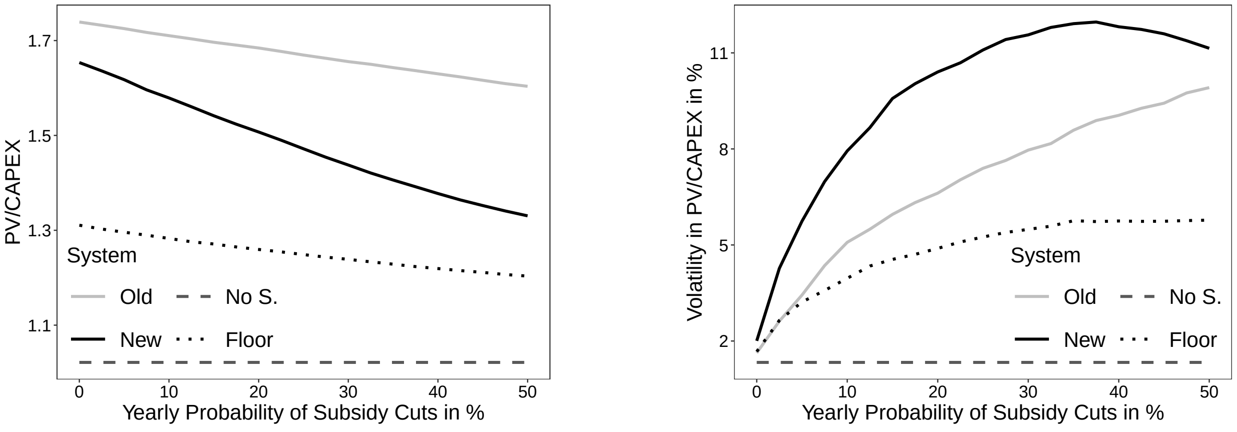


(a) Changing wind speeds

(b) Wind speeds and volatility

Figure F.3: Uncertainty in subsidies and the variable premium

Figures F.3a and F.3b show uncertainty in the subsidy compensation under different distribution schemes. Next to the old, new and no subsidy case, I apply a variable subsidy scheme (denoted as *Floor*), which guarantees a minimum of 40€/MWh for a ten-year period if power prices are below. The assumption from the base in Table 1 Panel D are partly redefined by Table 2. The simulation varies default probability as denoted by λ. Each data point in the graphs represents the mean or standard deviation of $PV/CAPEX$ over 1000 draws. As the subsidy-free system (No S.) is not subject to subsidy distributions, it is not affected by default probabilities in subsidy cuts.



(a) Uncertainty in subsidies

(b) Subsidy defaults and volatility

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A Corpus-Based Cross-Linguistic Study

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