Aalto University
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ECONOMIC CHARACTERISTICS OF POWER PURCHASE AGREEMENTS

Master's Thesis
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Abstract of master's thesis

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Abstract

Renewable energy forms an increasing share of global electricity production. Renewable production holds near-zero marginal costs, making its production decisions mostly exogenous, controlled by weather. The high capital intensity of projects makes output prices crucial from the viewpoint of the project developers, operators, and financiers.

Power purchase agreements – PPAs – were born to fix long-term prices for a part of production of renewable energy projects, partly to calm financiers' worries about price risk. In terms of financial economics, a PPA can be described as a forward contract with continuous delivery. This continuousness is reflected in a skewness in time-risk profile compared to a traditional forward or futures-contract.

Since corporate PPAs are of fixed delivery volume, during low production weather producers must purchase a possible production deficit from the general electricity market. These purchases, which are called spread covering, will systemically increase within specified electricity market areas. The effect yields from the correlation of production across renewable electricity producers.

From the perspective of the spot-market – the general electricity market – the result is likely an increased price volatility. The volatility is higher the closer to each electricity market hour new information on spread covering is revealed to the general market. This effect arises from an increasing rigidity of price elasticity of demand when moving time-wise closer to consumption, since industrial processes etc. have less time to adjust their use.

A PPA is not an optimal way of handling uncertainty, neither for renewable energy producers, for the technical functioning of the general electricity market, nor for common utility. This is due to three main factors: (1) Increased general market volatility caused by spread covering; (2) Faulty incentive structure between the parties; (3) Inefficiencies and moral hazards caused by incomplete or asymmetric information on production risk.

A recommended solution to avoid the increasing risks of PPAs – and renewable electricity – would be to make drastic changes to the electricity markets. A recommendable way would be to approach the issue through Wolak's (2022) standardized fixed price forward contract, and to introduce a transparent, comprehensive electricity derivatives market. This would allow for global risk allocation solution to a problem arising from cointegrated weather in markets with limited geography.

Keywords Power purchase agreements, renewable energy, energy economics

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Tiivistelmä

Uusiutuva energian osuus sähköntuotannosta kasvaa kaikkialla maailmassa. Uusiutuvan tuotannon rajakustannus on lähellä nollaa, jolloin tuotantopäätös on pitkälti sään eksogeenisesti määrittämä. Hankkeiden korkean pääomaintensiteetin takia kehittäjien, operaattoreiden sekä rahoittajien näkökulmasta sähkön myyntihinnat ovat kriittinen tekijä.

Pitkäaikaiset sähkönmyyntisopimukset (engl. power purchase agreements, PPA) syntyivät, jotta osa uusiutuvan energian hankkeen tuottamasta sähköstä saataisiin myytyä kiinteään hintaan. Sopimusten tarkoituksena on vähentää rahoittajien huolta myyntiin liittyvästä hintariskistä. Rahoituksen taloustieteen termein PPA-sopimukset voi ymmärtää forward-sopimuksina, joissa toimitus on jatkuva. Jatkuvuus näkyy arvonmuodostuksen riskirakenteen vinoumana suhteessa tavalliseen forwardiin.

Yritys-PPA:ssa toimitusmäärä on yleensä kiinteä, jolloin tuottaja joutuu vähätuotannollisina ajankohtina ostamaan puuttuvan tuotannon yleisiltä sähkömarkkinoilta. Tyypillisellä, säätilaltaan epätäydellisesti hajautetulla sähkömarkkinalla nämä sopimuksenkattamisostot tulevat lisääntymään PPA-sopimusten yleistyessä.

Yleisen sähkömarkkinan näkökulmasta kattamisostojen lisääntyminen tulee kasvattamaan sähkön markkinahinnan vaihtelua. Hintavaihtelu on sitä suurempaa, mitä lähempänä kutakin sähkönsiirtotuntia markkinaosapuolet saavat uutta tietoa kattamisostoista. Tämä johtuu kysynnän hintajouston jäykistymisestä sitä mukaa mitä lähempänä ajallisesti itse kulutusta ollaan, koska teollisuusprosesseilla ym. on vähemmän aikaa mukauttaa toimintaansa sähkön hinnan mukaan.

PPA on kaukana ihanteellisesta järjestelmästä epävarmuuden vähentämiseksi uusiutuvan sähkön tuottajien, yleisen sähkömarkkinan toimivuuden ja yleisen hyödyn kannalta. Tähän on kolme keskeistä syytä: (1) Sopimuksenkattamisostot lisäävät sähkön hinnan vaihtelua; (2) Osapuolten välinen kannustinrakenne on haitallinen; (3) Epätäydellinen, epäsymmetrinen tieto tuotantoriskeistä aiheuttaa tehottomuutta ja moraalikatoja.

PPA-sopimusten – ja uusiutuvan energian – kasvavia riskejä voitaisiin välttää tekemällä suuria muutoksia sähkömarkkinaan. Suositeltava lähestymiskulma tällaiseen muutokseen olisi Wolakin (2022) suosittelema standardoitu kiinteän hinnan forward-sopimus, yhdistettynä läpinäkyvän, kattavan sähköjohdannaismarkkinan luomiseen. Tämä mahdollistaisi kansainvälisen riskinhajautusjärjestelmän ja olisi ratkaisu ongelmaan, joka liittyy pohjimmiltaan sään yhteisintegroituneisuuteen maantieteellisesti rajatuilla sähkömarkkinoilla.

Avainsanat Pitkäaikaiset sähkönostosopimukset, uusiutuva energia, energiataloustiede

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1. Introduction

As the global effort of tackling climate change intensifies, most countries, including Finland (Ympäristöministeriö, 2021) have ambitious goals in reacting to the global phenomenon. Shifting toward green energy sources is vital for maintaining the standard of living in developed countries, but also for striving toward global prosperity.

Renewable energy, a subgroup of green energy, does induce its own set of challenges. Its growing share in the economy increases the meteorological sensitivity of power systems (van der Wiel et al., 2019). As electricity must be consumed as it is produced, higher weather-dependent supply volatility may be difficult to handle for short-term demand elasticity. The implication of this is higher price fluctuations, which in is commonly seen as a burden for risk averse market actors.

From renewable energy producers' point of view, this increasing volatility in revenue stream is a problem. Renewable energy projects, such as wind farms and solar parks, are highly capital intensive. They hold almost no marginal costs of production, leading to high leveraging and thus high capital costs. With high capital costs in relation to overall cost structure, renewable energy projects are vulnerable to income stream uncertainty induced by price volatility.

Financiers prefer a steady stream of revenue. To reach lower capital costs caused by this preference of financiers, project developers and operators have opted for financial contracts to find stability through fixing future prices.

Financial derivatives can be divided into publicly and privately traded contracts. In electricity markets, the main instrument of the former is the electricity futures contract, whereas in the latter, the power purchase agreement holds the spotlight.

A power purchase agreement – or a PPA – is a long-term financial contract held between a producer and a buyer of electricity. The typical corporate PPA has a length of 5-20 years, during which a continuous, fixed amount of electricity is delivered at a fixed price. Even though PPAs are becoming increasingly individualized and complicated, these basic characteristics still hold to a large extent.

As the volume of electricity delivery in a PPA is fixed and renewable electricity production is highly volatile, there are bound to be times when the producer cannot cover its commitments in the PPA – to deliver the promised amount of electricity from its own production. In such situations, the deviation between contracted and produced volume is bought from spot-markets, usually by the producer (FWPA, 2019).

From the standpoint of economics, some obvious questions arise: How does this “spread covering” affect the electricity markets? As weather is geographically correlated, and these spread covering induced demand spikes increase with higher share of weather-dependent electricity, will there be larger problems ahead? If so, how should electricity producers approach this price risk? Should governments control PPAs to protect the general electricity market? What is driving the demand increase for PPAs?

Renewable energy was a marginal issue for a long time, which is why these questions have not been thoroughly researched yet. As governments hurry for an increased green electricity production, effects of PPAs should be investigated to avoid both their possible adverse effects, and governmental intervention of an ever-increasing stock of active private contracts.

This thesis explores the economic nature of power purchase agreements, the financial structure behind them, and the effects they have on the general electricity market. The main research questions could be formatted as:

1. What are power purchase agreements from the viewpoint of economics?
2. What effects power purchase agreements have on the general electricity markets?
3. Are PPAs aligned with energy policy from the economic standpoint, and are there better alternatives?

As very little economic research exists on the subject of PPAs, I will start by explaining the instrument in more detail before taking a look at the base theories of risk and finance. Then, I will extend some basic financial economic theory to the PPA and reflect on the relationship between the general electricity market and PPAs.

In the latter half of this thesis, I will continue with a comprehensive literature review on the scarce economic research on PPAs. Previous literature is discussed a bit unconventionally, paper by paper, due to its scarcity. I will also investigate the relevant research in surrounding academic fields (mostly engineering), inferring, and interpreting their results in economic terms.

The thesis will be concluded by interpreting the results found, which will help to define answers to the research questions. Finally, some policy implications will be introduced along with suggestions for further research into power purchase agreements.

2. The Power Purchase Agreement

This section aims to give the reader a general understanding of power purchase agreements. The first subchapter explains typical contractual specifications served with some descriptive statistics on the side. The second subchapter gives some preliminary technical specifications, laying the groundwork for chapters 3 and 4.

2.1. The PPA in general terms

A power purchase agreement, or a PPA, is a long-term power transaction contract with continuous delivery from a producer of electricity to a buyer – the "project off-taker". A typical length of such contract varies between 5-20 years. The price of the electricity units used is fixed, or sometimes structured as "straddles". The volume of electricity covered by PPAs are usually fixed to a continuous linear stream. (CEER, 2021; Worldbank, 2021)

In other characteristics, PPAs are highly individualized to serve the needs of the related parties. These characteristics include technical specifications and division responsibilities in hazardous scenarios. One such scenario is a quantity shortfall, where the producer is not able to produce the contracted volume. Most often in such scenarios the producer is set to purchase the remaining power – the spread – from the general electricity market (the spot-market). (FWPA, 2019)

For an electricity producer, the purpose of a PPA is to provide financial stability by ensuring steadiness of revenue in a market with traditionally volatile spot-prices. From the producer's viewpoint, a PPA is often a prerequisite for external project financing – or at least a beneficial factor in securing cheaper money (Niklaus, 2021).

Renewable energy is more capital intensive compared to other forms of electricity production. Since they use less intermediate products, capital costs form a larger share of overall lifetime costs (Best, 2017). In addition to a diminished ability to time production with respect to prices, higher capital costs can be interpreted to cause PPAs to be particularly common in renewable projects.

From the buyers' perspective, a PPA is a handy way to reach toward carbon neutrality goals in their energy consumption. Compared to building their own production, signing a PPA with a renewable energy producer is a cost-efficient way to acquire the electricity for corporate operations, the environmental credits, and PR advantages of green energy. (Jin et al., 2018)

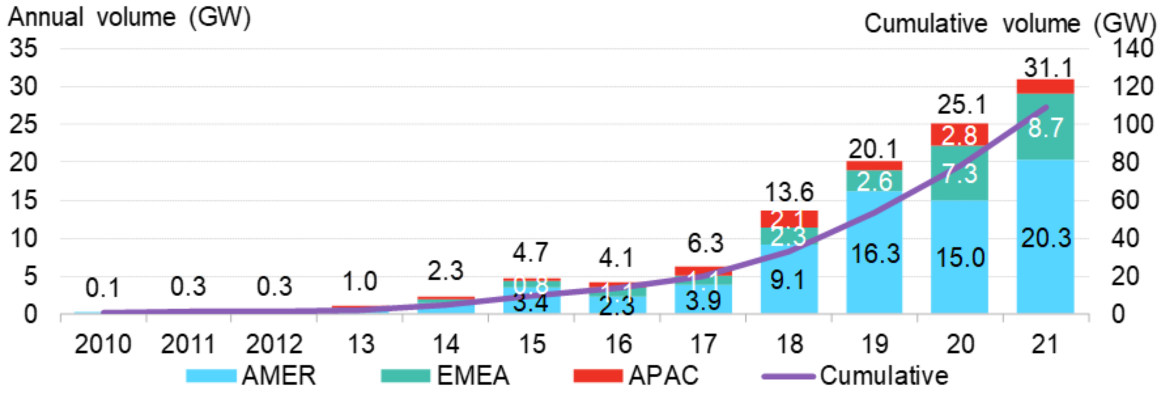
Power purchase agreements can be roughly divided into two categories: Physical and synthetic PPAs. In physical PPAs a physical delivery of electricity is included, whereas in a synthetic one it is not. Physical PPAs make up the majority of European PPAs, including in the Nordic area. They will therefore be the focus of this thesis.

Volume-wise, the vast majority of physical PPAs are settled through a third actor ("agent"). These are called *sleeved PPAs*. In sleeved PPAs, the agent takes care of the balance of power, handling the selling of excess electricity and the covering of spreads on behalf of the producer.

PPAs can be written directly between the end-user of electricity, usually called "corporate PPAs", or with a utility that sells that electricity forward to its customers, a "utility PPA". Utility PPAs are usually made to cover the whole production of the producer, instead of a fixed amount. They are more common in America, whereas in Europe fixed-amount corporate PPAs are more common. (Wu & Babich, 2012)

To understand PPAs through the example of counterparts, in the realm of financial theory, PPAs can be considered continuous-transaction forwards. They are highly individualized, and there are no efficient secondary markets. Another comparison could be found in Finnish nuclear energy complex in Olkiluoto where the electricity buyers own the projects themselves under the consortium Teollisuuden voima (TVO, 2021).

The use of corporate PPAs has been growing by an annual rate of 20-50 % for the last five years. In 2021, Bloomberg New Energy Finance estimated the global PPA volume to stand at 31.1 GW annually, which in EU average electricity price for non-household consumers (H1/2021) would roughly equal € 23 billion. (Eurostat, 2022; Henze, 2022)



*(AMER = Americas, EMEA = Europe, Middle East and Africa, APAC = Asia-Pacific)

Figure 1: Global corporate PPA volumes, 2010-2021 (Henze, 2022)

Glancing into individual European countries, Wind Europe (2022) reports an accelerating increase in renewable corporate PPA volume in most countries. Spain, Germany, Sweden, Netherlands, Finland, and UK saw the highest increases in capacity in 2021.

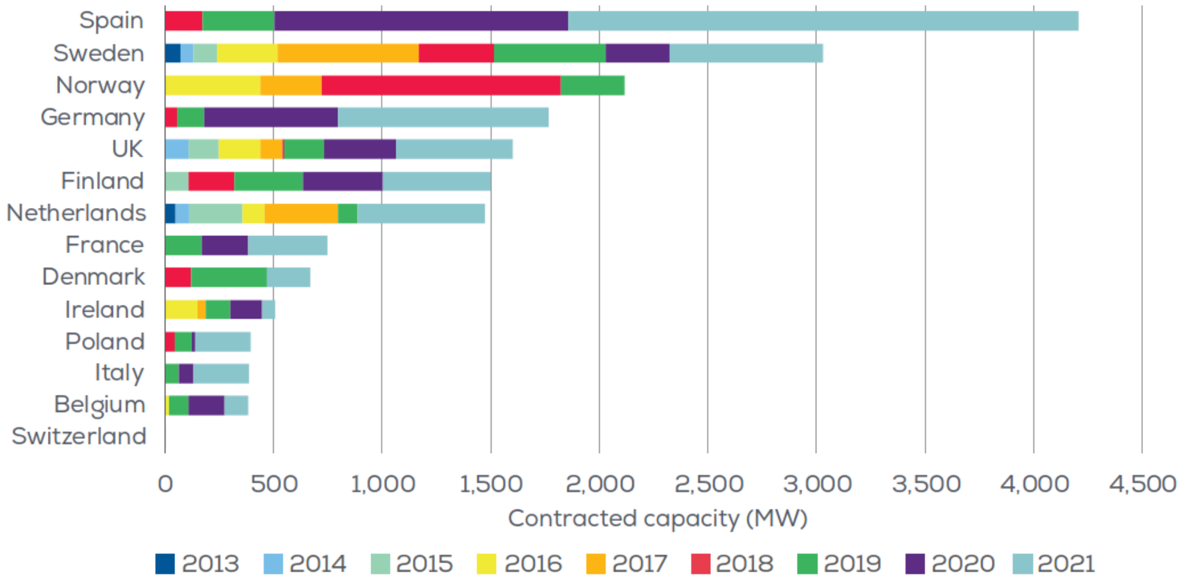


Figure 2: European renewable corporate PPA volumes 2021 (WindEurope, 2022)

Spain's dominance is rooted in high capacities of new solar energy alongside onshore wind. UK, Germany, and France are in the forefront of offshore wind investing, which is reflected in their numbers. Whereas in Europe, PPAs were mostly used in onshore wind energy, their use has spread to solar and offshore wind, as their utility-scale utilization has become financially more viable.

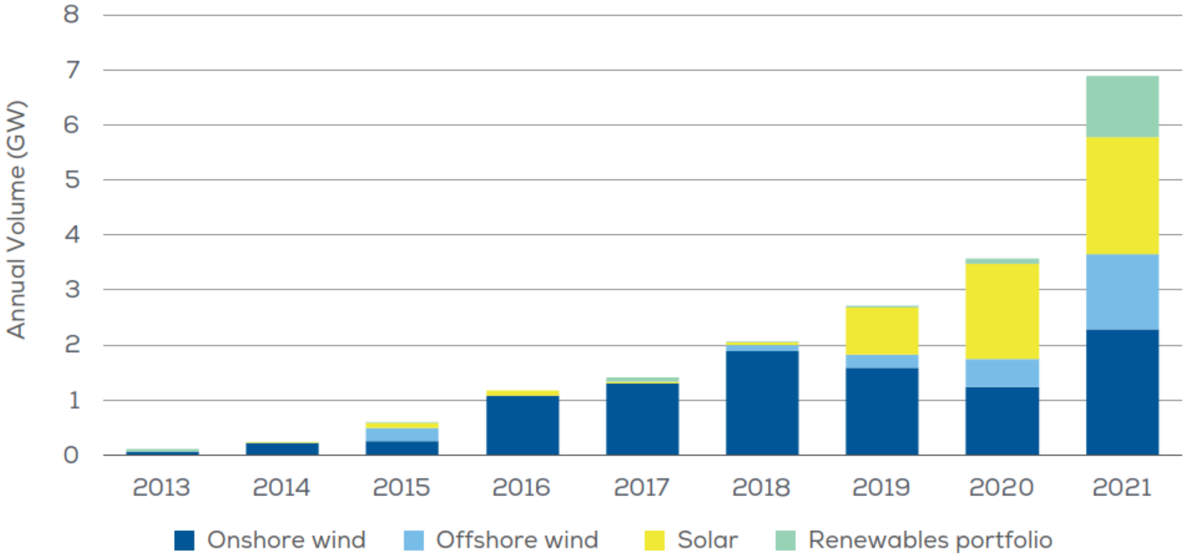


Figure 3: Sources in renewable corporate PPAs (WindEurope, 2022)

Off-takers, or buyers, of corporate PPAs expand throughout sectors. Highest shares are held by sectors with energy as a significant input product. Predictable and stable consumption volume contributes for an industry’s interest in PPA participation.

Figure 4 shows the distribution of PPA off-takers by sector. ICT and heavy industry make up the majority of consumers. The former, more specifically, consists mostly of data centres and similar stabile functions.

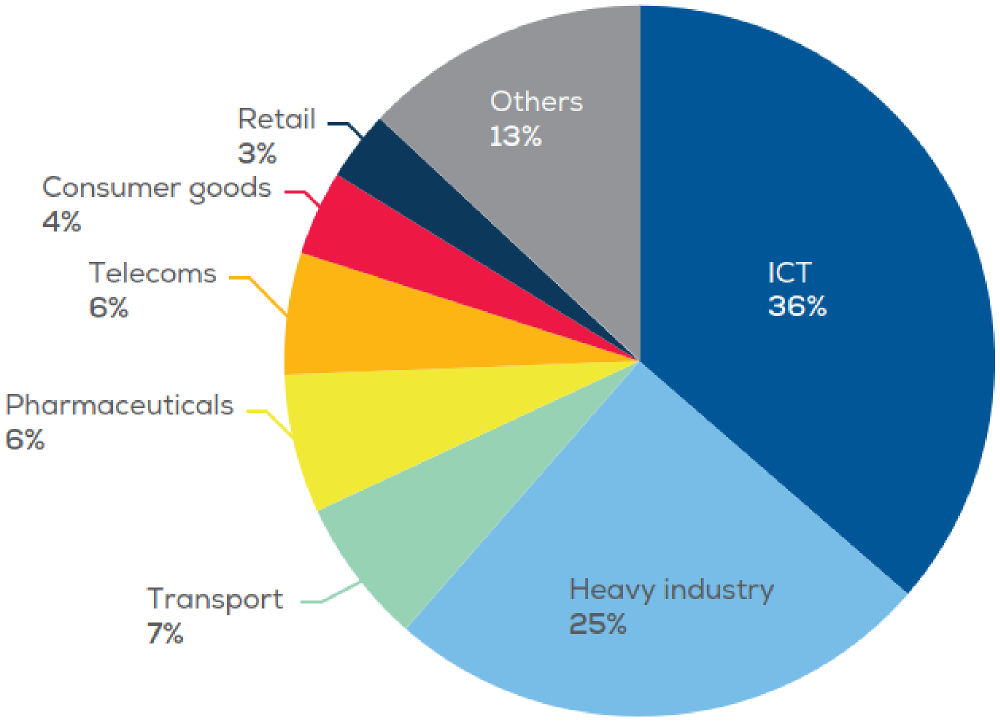


Figure 4: Off-takers of renewable corporate PPAs by sector (Best, 2017)

2.2. Preliminary technical aspects of a PPA

From the producer’s viewpoint, we can further exemplify a PPA with Figure 5, which represents simulated power production of a renewable energy project in megawatts (MW) for each hour for a month. Production is shown in green and contracted PPA volume in red. The producer will sell all of the most certain production via PPA, and the excess production to spot-markets.

The main research question of this thesis jumps in at *Production < PPA volume*, where production suddenly does not cover the entire PPA commitment. Here the spread – the area between production curve and PPA box – will have to be purchased from the wholesale market.

Figure 5: PPA example

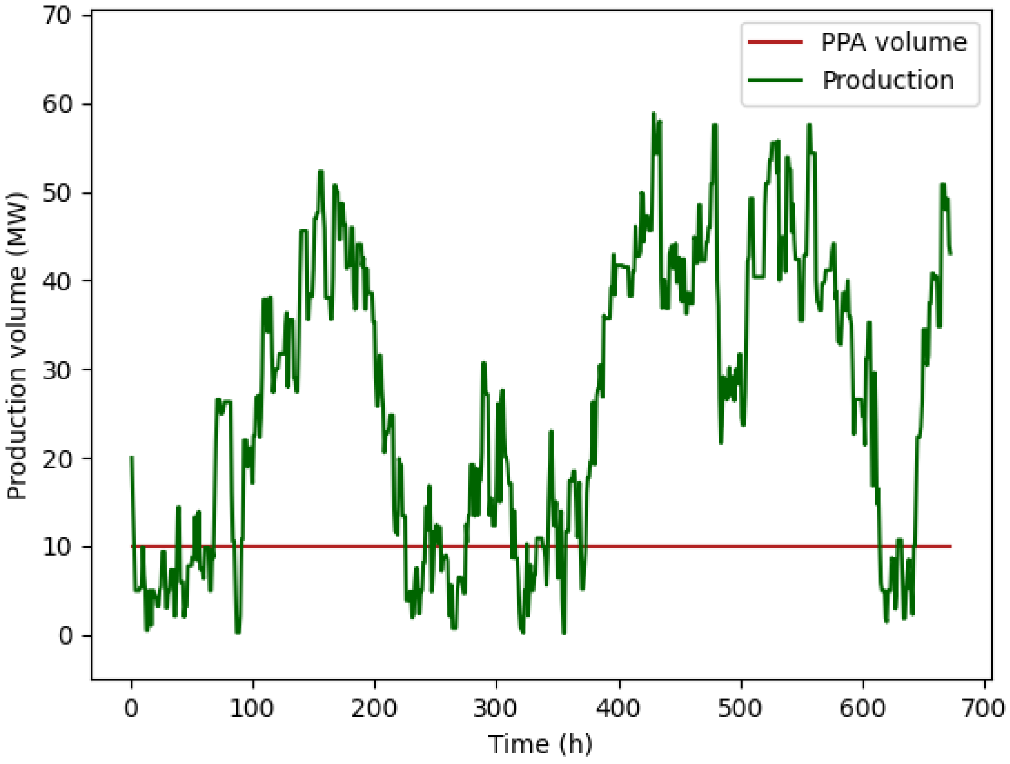


Figure 5: Simulated production of a PPA-tied wind farm

The monthly production in MWh is the sum

$$\sum_{0}^{t} Production$$

The revenue of the project without a PPA would be just the production of the farm multiplied with the corresponding price vector for each hour. This can be described in continuous terms as

$$\sum_{0}^{t} Production \sum_{0}^{t} SPOTprice$$

or

$$x' p_{SPOT}$$

where *x* is vector for production volume for each hour, and *p* the corresponding price vector.

However, if the project holds a PPA, the prices received by production will consist of the spot-prices for *Production > PPA* and, PPA revenue and spread covering costs when *Production < PPA*. So, the revenue stream of a wind farm with a PPA can be described as the vector *R:*

$$R = y'p_{PPA} + (x - y)'p_{SPOT}$$

where y describes contracted PPA volume and p_{PPA} the (constant) contracted price. The firm's problem of a wind farm with a PPA can thus be written as

$$\max \pi = R - C = R - x'c - F$$

$$= y'p_{PPA} + (x - y)'p_{SPOT} - x'c - F$$

where π describes a profit scalar of the project. Total costs *C* are divided to operating costs *c* that scale with production, and fixed costs *F*. In a completely certain world, any project with $\sum \pi > 0$ would hold value and be executable.

A relatively unique attribute that renewable energy has within its field is very low operating costs *c* as a share of total costs *C*. This means projects do not need to run down operations even in times of very low revenue streams arising from low market prices. Therefore, depending on down-running costs, a wind farm without a PPA would run down its operations at $p_{SPOT} \approx 0$.

A project with a PPA does not hold the downward price risk due to partially fixed prices from the PPA. However, if a partial down-running is possible, any excess production over contracted volume would be minimized at negative prices.

In addition, a project with a PPA faces a unique problem arising from the negative correlation of prices and production volume. This means that at times, when PPA-contracted volume exceeds production, spot-prices tend to be high. At hours, when $y > x$, the wind farm must be a net purchaser in the spot-markets, and those prices tend to be at a higher price than selling that volume to the PPA off-taker.

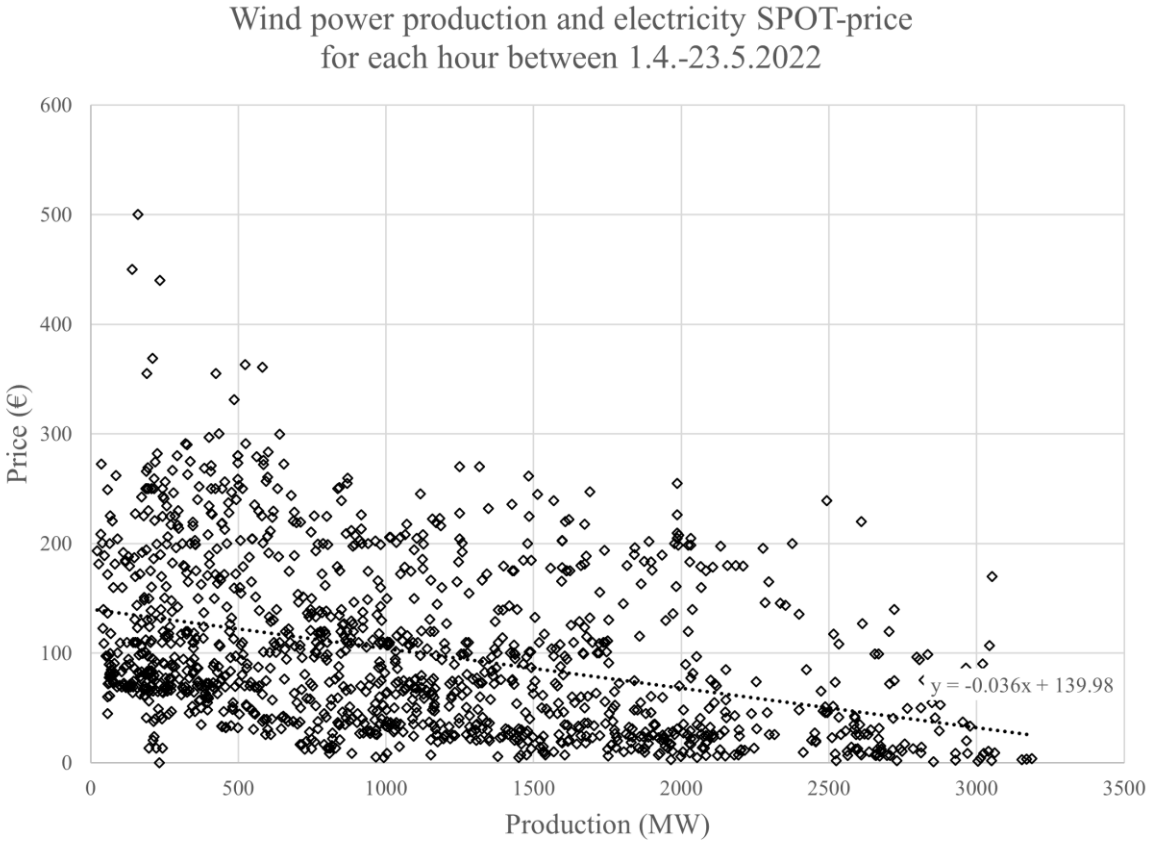


Figure 6: Wind power production and electricity price

To quantify the phenomenon, let's look at hourly domestic wind power production and electricity spot-prices from the period 1.4.-23.5.2022. We can find a correlation coefficient of -.37, while a simplistic linear fitting finds a 3.6 eurocent drop in electricity SPOT-price for each megawatt of increased wind power production.

If production diminishes to zero, the project must purchase the whole PPA volume from SPOT-markets. If this is the case, the revenue vector reaches

$$R = y'(p_{PPA} - p_{SPOT})$$

leading to negative revenue if $p_{PPA} < p_{SPOT}$.

This example will act as good preliminary information, as we proceed to determine the economic characteristics further in the following chapters.

3. Economics of risk

Classical microeconomic theory builds on the foundation of the risk averse consumer and the risk neutral firm. This risk neutrality is often argued with the presence of a perfect market, in which firms have sufficient access to capital. Owners can diversify their investments, so even the ultimate fluctuations of a single owned firm's value do not cause panic. (Sandmo, 1971)

When the assumption of risk neutral firm is lifted, firms will try to avoid uncertainties in their operations. Uncertainty can occur, for example, in inputs or outputs of production – either in quantity or price. In presence of such uncertainty, there will exist a risk premium, which a firm is willing to pay to get rid of said uncertainty. The need for insurance markets arises.

3.1. Risk in a two-side setting

A firm will purchase insurance for a price lower than or equal to its willingness to pay for each risk. Such insurance could not only be a contract between the firm and an insurance company, whose business revolves around having a lower risk aversion than firms and diversification of such risks.

The insurance can also be internalized in operational business contracts. If there is a trade between two risk averse firms, say, in a commodity with a volatile market price, the trade can be designed to use a fixed (or other less risky) price format. If the firms differ in their risk preference, an equilibrium price will formulate in favour of the less risk averse party.

In essence, a premium over the average of the volatile market price will be claimed by the party with a lower degree of risk aversion. In an aggregated market, the same outcome will arise. (Sandmo, 1971)

The same can be applied to PPAs as well. The buyer and seller of a PPA settle for a price, which reflects their risk attitude toward the price of the contracted electricity. This risk attitude can be seen in the premium of electricity price – that is, how much lower (or higher) the price of electricity is in the PPA compared to forecasts of the general market.

3.2. Commodity hedging

Securing commodity transactions through financial contracts has been a common practice since the 17th century, if not even longer. These derivative contracts give firms insurance for the future value of their inputs, or outputs, offering stability for long-term business planning.

Firms use commodity hedging to secure their input prices. This is especially important for companies with a cost structure highly dependent on one input. Such characteristic is common in fields such as traffic, heavy industry, and data handling.

The airline industry is a widely used example for their hedging of jet fuel prices. In the 00's, most companies locked in their kerosene prices ahead of time. However, as financial theory reached boardrooms and some companies saw success with abolishing the practise, the industry in the U.S. in particular have started to shift their paradigm during the last decade. Owners saw price hedging as an unnecessary expense with the practising costs and premiums, since they could themselves achieve the same effects by diversifying their investments (Mäntyvaara, 2019).

Major European airlines maintained their hedging practises. The most recent crises affecting kerosene prices have shown them both pros and cons of hedging activities (Dunbar & Karwal, 2022; Dunbar & Manpreet, 2020).

The same lessons stand for electricity markets, as well. Determining a price hedging strategy as good or bad with the benefit of hindsight is always foolish. Identifying the always subjective willingness to pay for risk mitigation and comparing that to premiums at the time of deciding a hedging structure is the objective way to approach the issue.

We will take a quick glance at the relevant building blocks for the latter half of the next chapter. The four major tools in commodity hedging are futures contracts, forward contracts, options, and swaps. With these, businesses can modify their financial risk structures quite flexibly.

3.2.1. Futures contracts

Futures contract is an agreement for a future transaction, in which the price used is set upon entering the contract. In essence, the value of the futures contract is zero at the time of signing, since it signals the best available information on the commodity's price at the time of transaction and a risk premium. The value of the futures contract starts to fluctuate as the market price outlook of the underlying commodity starts to differ.

Futures markets connect to spot-markets through this mechanism. The share of risk premium in the futures contract diminishes toward the execution date, at which point the value of the futures contract is simply the difference between spot-market price and the futures transaction price. (Gorton & Rouwenhorst, 2006)

Commodity futures are traded in public exchanges, such as Deutsche Börse's Eurex, the Chicago Mercantile Exchange, Tokyo Commodity Exchange, and various others. 95% of futures contracts are reverse traded by their expiration, meaning no physical delivery takes place. Instead, the parties just exchange the difference between the forward price and the spot-price at the execution date (HECHT, 2022).

Futures contracts are used in electricity markets as well, with Nasdaq Commodities being the main provider for the Nordic electricity market (Nasdaq, 2022). The existence of electricity forward price risk premia has extensively been studied in the field of financial economics, most notably by Longstaff and Wang (2004). Research on the issue extends to the Nordics, where premia have been found as well (Haugom et al., 2018).

There are two main pricing theories for futures contracts: Arbitrage pricing and pricing via expectation. They are not mutually exclusive, but their applicability differs. Both lean on the assumption of efficient markets, and that at the moment of signing a futures contract, its value is 0. For the sake of precision, the *value* of a futures contract is the value of holding a position in such contract. *Forward price* is the price of the parties have agreed to execute the transaction in the set date.

Arbitrage pricing can be used with a commodity that can be stored, such as a share of a company or oil. This is because arbitrage pricing relies upon the opportunity cost of holding the commodity as the seller, who is financially the short position holder. When using arbitrage pricing, the *forward price* of the futures contract can be set to equal

$$F(t,T) = C(t)e^{(r+u-q)(t-T)}$$

where F is the value of the futures contract at time t tied to the exercise time T, and $C(t)$ is the price of the commodity at time t. r is the risk-free rate, indicating the opportunity cost of holding the commodity, and u is the storage cost of the commodity. q is a possible dividend or an income yield. (Gottesman, 2016)

As electricity cannot, at least at the time of writing, efficiently be stored to an industrial capacity, arbitrage pricing is not relevant to electricity futures (or forwards, or PPAs for that matter) pricing.

Pricing via expectation simply ties the expected forward price of the commodity in question with the exercise (forward) price of the contract. Since they equal at the time of signing the contract, the only determining factor of the futures price are changing expectations in the forward price of the commodity in question.

$$F(t,T) = E\{C(T)\}e^{r(t-T)}$$

The *forward value* V of the contract starts to evolve after its signing at t, as expectations about the future start to differ. So, for some moment a in $t \leq a \leq T$,

$$V(a,t,T) = F_a(a,T) - F_t(a,T) = E_a\{C(T)\}e^{r(a-T)} - E_t\{C(T)\}e^{r(a-T)}$$

holds. Here E_a and E_t mean the price expectations in the subscripted moments of time.

3.2.2. Forward contracts

Forward contracts are similar to futures but tailored to meet the needs of the parties. When contracts are tailored for specified parties, however, they do not have liquid aftermarkets. The tailored subjects can be such as delivery place, time and method, etc.

Due to this characteristic, forward contracts do not have secondary markets themselves. This makes such contracts illiquid, therefore requiring specific exit-opportunities to be detailed.

The price setting mechanism of forwards is like that of futures contracts, but two more substantial risks occur: a liquidity risk and a counter-party risk. Both are typically priced as a premium on top of the price of a comparable futures contract.

PPAs are quite similar to forward contracts in the sense that they are individualized between the needs of the parties. However, the continuous execution of delivery differentiates the forward value from the one of a forward or futures contract. We will return to this issue in the subchapter 4.1.

3.2.3. Options and option strategies

Buy options and put options are financial instruments where the holder of the option has the right, but not the obligation, to buy or sell (put) a commodity at a set *strike price*. An “European” option limits the execution of the right to its expiration date, whereas an “American” option allows selling at any point until the expiration.

A market actor pays an *option price* to purchase the option, and gains money from the transaction if the *strike price* on which the actor executes their option is favourable compared to the *market price* of the underlying commodity at the time of execution. On the other hand, the market actor can also avoid their own exposure to the fluctuations of *market prices*.

Companies and financial actors can quite flexibly create a desired structure of their risk exposure to the underlying commodity via options. This can be achieved by combining option holdings with buy options and/or put options with different expiration dates and strike prices. Some examples of such strategies are different spreads, collars, and straddles.

Options are increasingly common in electricity markets, even though they have not yet landed in the Nordics. However, in mainland Europe, power options are provided by actors such as European Energy Exchange AG. A few studies have also been conducted on the subject, such as (Pineda & Conejo, 2013).

3.2.4. Swaps and contracts for difference

Swap-contracts and contracts for difference (CFDs) hold many similar economic characteristics, so I’m referring to them as one bunch.

They both tie a fluctuating price or an index to a reference rate. A market actor engages to pay or receive a payment subject to the development of the fluctuating price over the set reference rate. The counterparty benefits from securing the fluctuating commodity for the more stabile reference rate. However, some risk premium is typically baked into the contract.

In electricity markets, synthetic PPAs can be considered a type of commodity swap. The seller delivers its producer electricity to the common market, and buyer buys its from there. However, if the spot-market price is below the set PPA price, the buyer pays the seller the difference of the market price and PPA price (wise-versa, if the spot-price is above the set PPA price).

There is no mentionable previous research on synthetic PPAs from this approach. However, it is safe to assume that a risk premium is baked into the PPA price. As the environmental credits/guarantees of the produced electricity are transferred to the buyer, also an environmental/green premium could be argued to exist in synthetic PPA prices.

3.2.5. PPA and traditional derivatives

Power purchase agreements hold some of the same characteristics as the aforementioned derivatives. However, as PPAs are structured around continuous transaction, their geometric structure of risk premium is more front ended.

In addition to risk premium, PPAs can be interpreted to hold "environmental premium" as well. As the contract is designed to catch the most reliable part of production, an environmentally conscious buyer (or one that seeks utility from that label) finds value on the guarantees of origin provided. Therefore, renewable electricity can be classified as a semi-differentiated market from non-renewable electricity, even though the physical product is identical.

In this sense, PPA is like a forward contract that is tailored for the contributing parties. This also means that a PPA includes counterparty risk.

4. Quantifying the PPA

In this chapter we apply the principles from the previous chapter to PPAs. In the first subchapter, we define PPA as a derivatives contract, or more precisely, a forward with continuous transaction. In the second sub-chapter we look at the relationship with PPA and the general electricity market.

4.1. Forward value of PPA

To understand the effects PPAs have on the general electricity markets, their financial risk structure should be determined. In the current literature on PPAs, their characteristics as a derivatives contract have not yet been specified.

I argue that power purchase agreements should be approached as continuous-transaction forward contracts. Therefore, their forward price and forward value can be derived from the somewhat simplistic characteristics of futures contracts.

It is possible to think of a PPA as a library of futures contracts for each electricity market hour until its expiration. At the exact time of signing a PPA, its value is zero, as is that of a futures contract. Now if at a timepoint a in $t \leq a \leq T$ the expected future path of electricity prices differs, the difference between the original and new expectation for each hour forms the new value of the PPA, $V(PPA)$.

Later transaction hours of a PPA are riskier than the earlier ones, since the world can change more during the time between them. Therefore, those later hours must be discounted by a larger factor than the earlier ones. The result is that changes in expectations for the earlier hours of a PPA have a larger impact in PPA value than changes in expectations for the later hours.

Now $V(PPA)$ can be derived from the corresponding one of a futures contract:

$$V(PPA) = \sum_{b=a}^{T} V(a,b,t,T) = \sum_{b=a}^{T} F_a(a,b,T) - F_t(a,b,T) = \sum_{b=a}^{T} \frac{E_a\{C(b)\} - E_t\{C(b)\}}{(1+r)^{b-a}}$$

where $E_t\{C(b)\}$ is the expected market price for each hour *b* in $t \leq a \leq b \leq T$ at the time *t* of signing the contract, with *C(b)* being a vector of hourly prices for the duration of the PPA. $E_a\{C(b)\}$ is the corresponding new expected price path determined at time *a*.

Unlike an efficient futures contract, a PPA includes counter-party risk: If the counterparty is not able to execute the transaction, or the contract is completely terminated, the counterfactual is to sell those hours' electricity for the corresponding market price. The outcome includes two-way risk for the difference in PPA price and the market price.

The buyer of a PPA also benefits from the guarantees of origin, environmental credits etc. associated with renewables PPAs. If there exists counterparty risk, the market may not have renewable electricity available for those hours. From the sellers' perspective, there may not be excessive demand for environmental credits in the common market, an aspect that is included in the original PPA contract.

Therefore, counterparty risk x and an environmental premium n should be included into discounting:

$$V(PPA) = \sum_{b=a}^{T} \frac{E_a\{C(b)\} - E_t\{C(b)\}}{(1 + r + x + n)^{b-a}}$$

As PPAs expand for decades' worth of electricity market hours, their value function could be displayed as continuous:

$$V(PPA) = \int_a^T V(a,t,T)dt = \int_a^T F_a(a,T) - F_t(a,T)dt$$

$$= \int_a^T E_a\{C(b)\}e^{(r+x+n)(a-b)} - E_t\{C(b)\}e^{(r+x+n)(a-b)}\, db$$

which is the forward value of a PPA at time a in $t \leq a \leq T$. Now *C(b)* is a continuous function instead of a discrete sum.

When adjusting for the contracted load L (here "load" instead of "volume" for notational reasons), we can simply multiply the forward value.

$$V(PPA, L) = L \int_a^T E_a\{C(b)\}e^{(r+x+n)(a-b)} - E_t\{C(b)\}e^{(r+x+n)(a-b)}\, db$$

Power purchase agreements most often include a buyers' responsibility to cover possible spreads between a lower-than-PPA production from the spot-market. An additional term for the expected value of those could be added, yielding

$$V(PPA, L) =$$

$$L \int_a^T E_a\{C(b)\}e^{(r+x+n)(a-b)} - E_t\{C(b)\}e^{(r+x+n)(a-b)} - E_t\{S(b)\}e^{(r+n)(a-b)}\, db$$

where $E_t\{S(b)\}e^{(r+n)(a-b)}$ stands for the discounted expected cost for spread covering. Note that spread covering does not include counterparty cost, since it is executed in the liquid common marketplace.

If we want to find the premium for a unit of electricity (commonly €/MWh in the Nordics), we can divide by the remaining hours *T-a*.

So, finally, the (discounted) forward value for a unit of electricity in a PPA is

$$V\left(PPA, \frac{L}{T-a}\right) =$$

$$\frac{L \int_a^T E_a\{C(b)\}e^{(r+x+n)(a-b)} - E_t\{C(b)\}e^{(r+x+n)(a-b)} - E_t\{S(b)\}e^{(r+n)(a-b)}\, db}{T-a}$$

PPA forward value can be used by both sides of a PPA to analyse the value of their PPA compared to the counterfactual (the spot-market), and therefore to find the optimal PPA price. It could also be used in a scenario-based analysis to assess the risk structure of projects, project lifespans and counter-party risks.

It is noteworthy that, as in a futures contract, the forward value of a PPA at the time of signing it is 0. If it was something else, the transaction price in the PPA would be either over- or underpriced. This would obviously make the contract undesirable for one of its parties, and it would not be signed.

PPAs include expensive contract fines for withdrawing. A critical change in future price outlook could cause either side to see withdrawing from a PPA as a valid real option, even with some payments associated with the action.

4.2. The problem of randomized, exogenous production

Production volume of a wind or solar energy producer is exogenous, largely independent from any price mechanisms. As marginal cost of production is always close to none, only negative output prices would cause downrunning of production. In fact, the optimal solution for the producer's problem in wind and solar is to always either operate in full or halt operation completely.

A few problems arise from this detail of industrial economics. The following subchapters will discuss how the entire electricity market is affected by exogenous production decisions, and how PPAs in particular may further contribute to those problems.

We will first look at a hypothetical, simplified situation, where the PPA producer and off-taker form their own, closed, system. Afterwards, the learned lessons will be extended to an aggregated market setting in a realistic, geographically incompletely diversified electricity market with high shares of PPA-tied renewable energy production. Then it is possible to form arguments about the effects of PPAs on the general electricity market, and into aggregated utility in a broader sense.

4.2.1. A closed PPA ecosystem

Let's start closing in on the industrial economic angle by looking at a closed system. That is, one producer and one buyer. If this relationship is in the form of a PPA, the buyer would require a steady electricity supply, and hold no value to any additional supply.

Production volume is therefore only a matter of capacity, which in turn derives itself from weather conditions. Hence, production can be modelled as a draw δ from some distribution D inside the unit interval $(0, 1)$ – a fraction of maximal production (or nominal capacity) in ideal weather circumstances.

A draw of 0 would imply production Ψ to be null, whereas a draw of 1 would mean the project running in full nominal capacity Ω.

$$\Psi_t = \delta_t \Omega$$

To achieve a steady supply of electricity, for example for a PPA, the producer would need to assure offsetting production capacity. For example, if they are obligated to deliver an amount equal to a fraction f of their nominal renewable capacity, they would need to have a balancing stand-by capacity of $f\Omega$.

$$\Psi_t = \delta_t \Omega + (f - \delta_t)\Omega$$

$$= \delta_t \Omega - \delta_t \Omega + f\Omega = f\Omega$$

Assuming renewable energy production has a marginal cost of 0, and the balancing production has a marginal cost of some positive number a with no other variable costs, the producer will choose to use all the renewables production. Stand-by capacity will only be activated and used to the extend that is needed. That is, the producer's cost structure is

$$C_t = \begin{cases} 0 & \text{, when } \delta_t \geq f \\ a(f - \delta_t)\Omega & \text{, when } \delta_t < f \end{cases}$$

Looking at two scenarios out of infinite possibilities, examples 1 and 2, we can see the arbitrary nature of the cost structure the producer faces for a PPA-tied production Ψ:

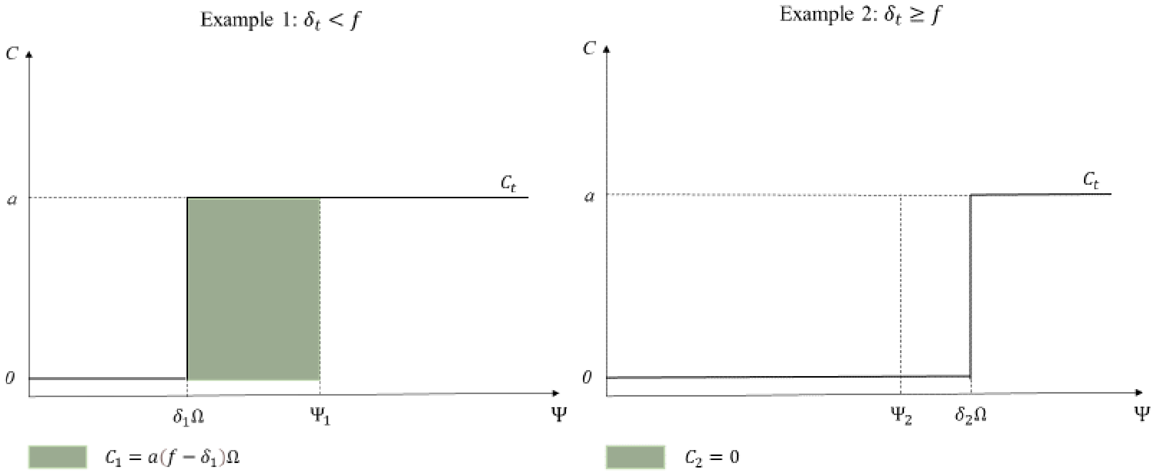


Figure 7: Closed ecosystem cost structure with exogenous production

It is worthy of noting that if the capacity of renewable production and PPA volume are increased, stand-by capacity must be increased by the same factor.

In practice, producers purchase the balancing capacity from spot-markets to cover their PPAs. The buy-side of a PPA often requires this electricity to either include guarantees of origin, or be renewable energy, as well.

4.2.2. Geographically incompletely diversified market

Let us focus on a market area where numerous renewable energy producers are competing. The producers would prefer operating without balancing capacity, whether it is theirs or purchased from spot-markets, due to its higher marginal cost.

In this case, no balancing capacity is needed, if

1. In the renewable energy industry, the term δ_t is independent and non-correlated across producers and time
2. The market area in question has sufficient transmission capacity
3. There are many producers

Even though the latter two requirements can be interpreted to be met in many markets, the first one is not (Vallée et al., 2007), etc. This means that some fraction F w.r.t. all renewable, weather dependent production, must be in reserve as a stand-by balancing capacity. As δ_t are one-to-one correlated across the producers, we find that $0 < F < 1$ for the aggregated market.

As the share of renewables in electricity production increases, and if price volatility is deemed undesirable, the need for balancing capacity increases. However, as renewable sources of balancing production are largely limited to hydroelectricity, the realistically utilizable capacity potential is largely in use in most developed electricity markets (Sipahutar et al., 2013).

To further exemplify this aggregated situation, we can approach it graphically. Imagine a simple general electricity market. Let's look at two situations, where:

A) The market has a high price elasticity of demand
B) The market has a low elasticity of demand

Price elasticity of demand typically decreases closer to the execution of consumption, including in electricity markets (Cialani & Mortazavi, 2018). This notion is quite simple to add to our inference. As we get closer to each electricity transaction hour, we move $A \rightarrow B$.

The aggregated supply curve shifts over time according to the weather conditions. Here ω_1 (black supply curve) indicates a low-production weather, whereas at ω_2 (red supply curve) renewable production is high. As the capacity factor δ_t differs between producers, the market can be described by a neat supply curve, the angle and curvature of which shifts with cost structures derived from weather.

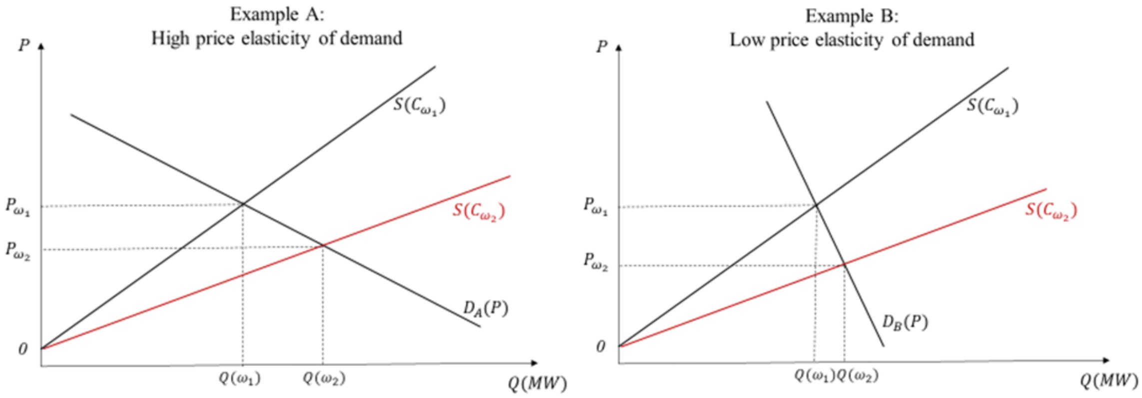


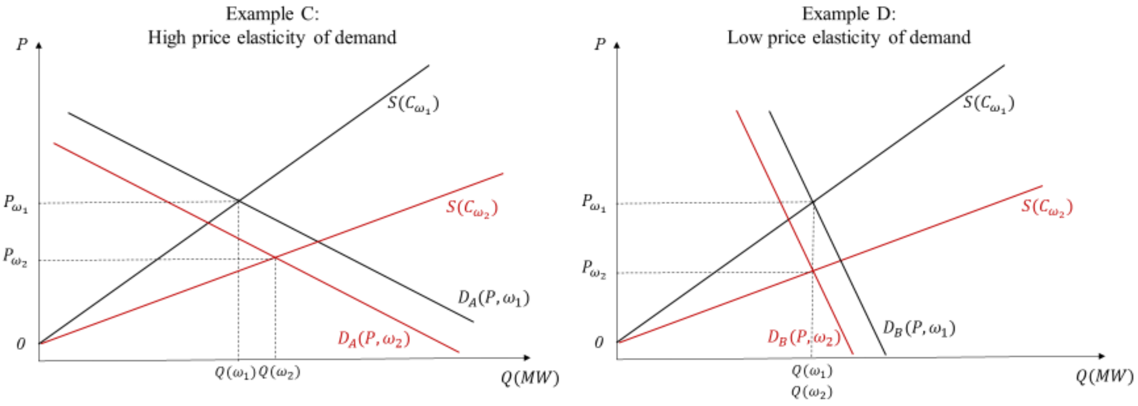
Figure 8: Aggregated market with exogenous supply variation

We see that in A with a higher price elasticity of demand, price stays much more stable and quantity of sold electricity varies more than in B. So, the more near-future electricity consumption is considered, the more the market shifts from A toward B. In addition, the higher the shifts in production, the higher the price volatility.

Now add to the above market example a notion of a separate PPA-market operating in the dark. At times of low production, sudden spread covering increases demand in the general marketplace.

What happens when PPA producers enter the marketplace at times of low production to cover their spreads, and to fulfill the capacity promised to the buyer? When adding the effects of PPA spread covering, demand is higher with lower production weather ω_1 ceteris paribus.

We can see that effect in examples C and D with an additional low-production demand curve. The price fluctuation between the states of weather is amplified by the demand shift. Graphically, the effect is seen in $D(P, \omega_2)$ and $S(\omega_2)$ having an intersection at a lower price P than $D(P, \omega_1)$ and $S(\omega_2)$.



Example C:
High price elasticity of demand

Example D:
Low price elasticity of demand

Figure 9: Aggregated market with exogenous supply and spread covering variation

We can see that with increased demand at times of lower production weather, and decreased demand during higher production weather, price volatility is increased from examples A and B.

It is worthy of noting that if we were to add natural convex curvature to the graphs, we would see an exponential volatility growth when enlarging demand and production shocks. PPAs may end up a source of increased volatility if the need to spread cover from spot-markets increases, and if balancing capacity does not grow accordingly swiftly enough.

4. PPA literature

In this chapter, I will focus on the limited amount of relevant research on power purchase agreements. Even though the use of PPAs has been growing at 25-50 % annually for the last 5 years (Henze, 2022), there is still quite little economic research on this topic. For this reason, papers from related fields are included. This is also the reason why the literature review is conducted separately and paper by paper.

When it comes to the research question on the effects PPAs have on the general electricity market, I am yet to find previous literature. Therefore, this literature review will focus on the research closest to the question and on interpreting the implications to economics.

I will dedicate individual subchapters to the most relevant papers, and one to the rest of the field.

4.1. Baik and Doshi (2021) on PPA price formation

In countries with environmental credit systems, the offtaker (electricity buyer) in a PPA owns the credits. Therefore, the environmental premium of electricity is internalized in a PPA. (Baik & Doshi, 2021)

The negotiation process of a PPA can be analysed from both the perspectives of the seller and the buyer. Since a PPA reduces price uncertainty for both parties, PPA price formation is dependent on the risk aversion of each party.

Baik and Doshi had an access for time-development of PPA and wholesale (spot) price in Texas, U.S. They report their data to have been collected from Berkley Lab, Utility-Scale Solar 2020 and S&P Global Market Intelligence:

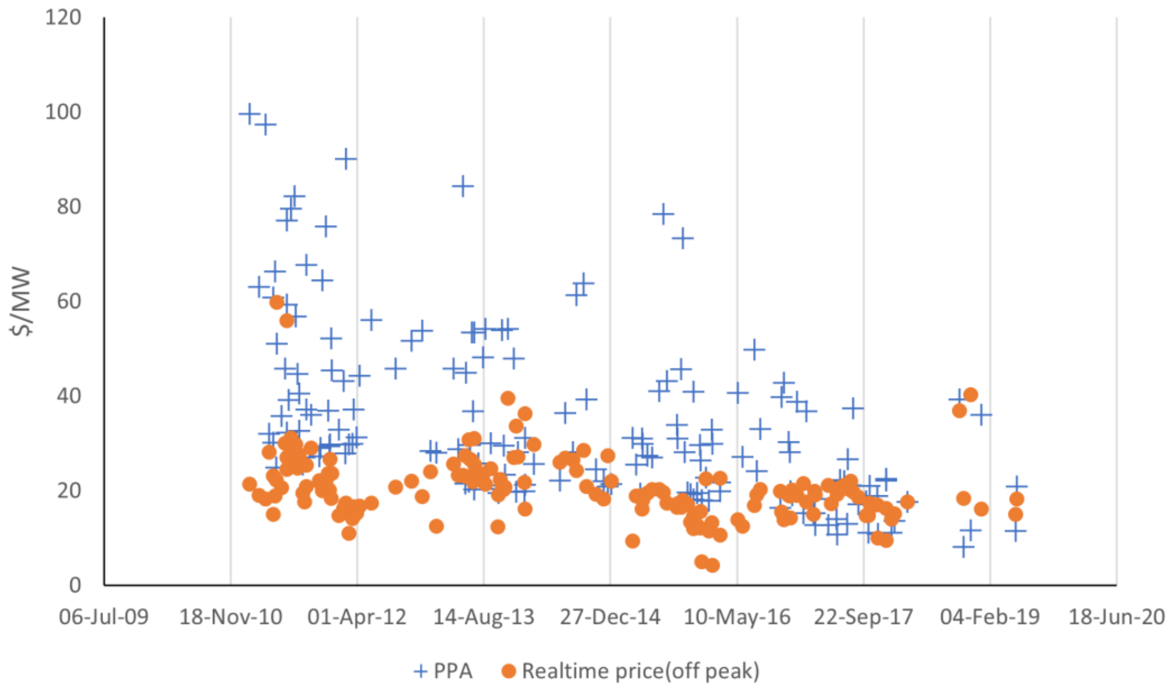


Figure 10: Wind PPA prices and Wholesale electricity price (Baik & Doshi, 2021).

Although the authors do not report quantitative results in terms of correlation, they do report a decreasing gap between the spot-price of electricity and PPA price. Reasons for this are not studied, though my intuition suggests it to be due to a typical adjustment process based on asymmetric information in a new market.

The price gap is claimed to be caused by several factors. One of these is sited to be the private bargaining process of the parties in a PPA. Developments in their risk preferences can be seen as another factor for the tightening gap.

The authors state several commonly recognized exogenous price-setting factors of a PPA. Among these are market (spot) price, its variance, and quantities of demand and supply. Spot-price includes *price risk* (described by x in this thesis' subchapter 4.1)*,* which the authors argue can affect the relative attractiveness of a PPA contract.

Volumetric risk is defined as the gap between produced volume and contracted volume. As defined in chapters 2 and 3, this gap (spread) is covered by the seller of the PPA by purchasing from the spot-market. This causes the volumetric risk to be faced by the seller.

Baik and Doshi also state contract length as another factor of PPA price, assuming a negative effect due to typically higher time-variance price sensitivity of the seller. This is aligned with the financial economic analysis in chapters 3 and 4.

The authors proceed to develop a model for price setting through exogenous factors. The model determines the comparative statics of exogenous factors affecting the participation rate in the PPA market. The directions are found to be (Baik & Doshi, 2021):

Table 1: Direction of PPA market participation rate

Participation	Seller	Buyer
Market price	-	+
PPA price	+	-
Price volatility	+	+

Proceeding to their empirical part, Baik and Doshi conduct an empirical section, determining running an OLS regression. The authors report the following table:

Table 2: Baik and Doshi (2021) OLS results (collapsed)

Dependent Variable: PPA Price ($/MWh)	
Contract length	1.093
	(0.743)
Mean of wholesale electricity price ($/MWh)	7.433***
	(0.906)
Std.Dev. Of Wholesale Electricity ($/MWh)	-8.357***
	(0.549)

(See appendix for the complete table
for the rest of the variables and notes)

N=56, $R^2 = 0.952$(?)

Notes: Significance: * $p<0.05$, ** $p<0.01$, *** $p<0.001$

The authors' main inference considers the capacity grouping, where we see a non-linear development, most interestingly from the third to fourth quartile (in complete table, found in appendix). Two possible factors for this are stated: Quantity discounts and higher participation rate in PPAs for larger projects.

As can be seen in Table 2, the relationship between PPA-prices' and wholesale spot-prices are observed to be positive, as the theoretical model's comparative statics (Table 1) suggest. The OLS suggests a PPA price increase of ~7.4 $/MWh for each dollar increase in wholesale price. The quantity of the relationship seems high and could be criticized on cointegrated variables – retail electricity prices are used as a separate variable in the same regression.

Price volatility seems to decrease PPA price, aligning with the authors predictions that the seller is inclined to be more sensitive to price uncertainty. This observation is also in line with this thesis, where I argued the seller to be more risk averse.

As the OLS approach is likely to exclude endogenous factors, the authors approach the issue through the Heckman 2 Step model (Table 3).

Table 3: Results of the intensity equation from the Heckman 2 Step Procedure by Baik and Doshi (2021) (collapsed)

Dependent Variable: PPA Price ($/MWh)	
Contract length	0.588
	(0.356)
Mean of retail electricity price (Cents/KWh)	4.046*
	(1.579)
Std.Dev. Of Wholesale Electricity ($/MWh)	-3.535***
	(0.577)
Total Capacity (MW)	-0.077*
	(0.031)

(See appendix for the complete table
for the rest of the variables)

N=508, prob > wald chi^2 ~ 0

Results align with the OLS approach, although coefficients are of lower magnitude. This is likely due to the removal of wholesale prices – the problem seen with the OLS approach.

The authors formulate three policy implications: 1. Policies that target buyers affect the implementation and pricing of PPAs. 2. As larger capacity projects yield lower PPA prices, incentivizing large wind projects may be favourable. 3. Longer PPA contract lengths and higher spot-price volatility would attract more buyers who want to avoid market uncertainty.

I find 1 and 2 feasible, yet policy implication 3 seems insufficiently argued, as the regressions show a clear negative relationship between spot-market volatility and PPA prices. This implicates a higher sensitivity for uncertainty for the buyers, not the sellers, in the PPA market.

Another conclusion could be that sellers are more worried about price volatility in the front-end of a project than in the final years, whereas the buyers' sensitivities are rather constant over time. In my opinion, the time-structure of sellers' volatility would be well explained by the financing structure of wind projects. Lenders' covenants for active PPAs deactivate when loans are paid off. Loans, in turn, are rationally designed to paid off before the end of projects, as there is uncertainty in the lifespan of wind projects due to technical reasons.

4.2. Ghiassi-Farrokhfal et al (2021) on increasing PPA predictability

Like Baik and Doshi, this trio also discusses the two-sided optimization problem of opting to a PPA. In addition, they find policy recommendations to increase the predictability of PPAs via battery mechanisms.

The authors recommend introducing a quantity adjustment operator to power purchase agreements, in order to avoid moral hazard by the seller. Such hazards could occur in the form of misreporting production quantity predictions. A solution would therefore be to share the risk of production volatility between the parties. (Ghiassi-Farrokhfal et al., 2021)

Another technical solution would be to use batteries to increase the capacity of feasible PPA. In essence, some power could be stored in a battery system during high-production weather, and those storages could then be used during low production or maintenance. The authors develop a technical model for this and simulate results.

The main conclusions are that parameters of a PPA can be set as such that supply uncertainty risks for the buyer are reduced, while financial attractiveness is maintained for the seller. The authors claim that introducing storing capacity can be beneficial for both sides of the PPA. However, depending on clauses regarding faith of production beyond PPA capacity, setting a limitation on power storage may yield a mutually optimal outcome.

The effect of battery capacity and PPA extends to the purposes of this thesis. Renewable energy producers introducing batteries (or other forms of energy storage) also decreases PPAs' predicted effects on general electricity markets – the main problem identified in chapter 4.2. Not only is less surplus energy dumped there, but also less production deficit - based spreads need to be covered from the spot-markets. As an end result, a decreased market volatility is caused by a more stabile aggregate production.

4.3. Lei and Sandborn (2018) on wind farm useful life predictions using PPAs

As stated in previous chapters of this thesis, wind power projects are limited lifeline projects with high capital intensity. Modern wind projects have a predicted production frame of ~25 years (Gignac, 2020; Potter, 2021), a lifespan that is continuously extending with technological development. Wind farms do not continuously generate electricity for the whole of their lifetime, partly because maintenance must be conducted.

Maintenance can be divided into corrective and proactive maintenance, of which the former is conducted after failures occur, and the latter in either pre-determined intervals or ad-hoc basis when a risk of failure increases.

Lei and Sandborn discover the effects of optimal proactive maintenance on a wind project with PPA, compared with an 'as-delivered' (or spot-selling) revenue model. They conclude that projects with PPA have different optimal maintenance strategies, due to their responsibility to ensure promised delivery.

Whereas in 'as-delivered' projects maintenance breaks should be scheduled to times with as low a market price as possible, projects with PPAs should have the proactive maintenance conducted during high-productivity weather conditions. The difference in maintenance strategies exists also in clustering of maintenance – stopping multiple turbines simultaneously. (Lei & Sandborn, 2018)

Projecting the authors' rather technical analysis to the research question of this thesis, we can conclude that the optimal maintenance schedule of PPA wind project may increase the volatility of electricity market spot-prices.

In projects with spot-price revenue, optimal proactive maintenance is conducted during times of low market prices – in turn reducing aggregate electricity supply and thus increasing market price. In PPA-backed projects, such effect does not happen, nor does the exogenous volatility reduction

It is, however, worth acknowledging that low market prices and high-productivity weather conditions have correlation, reducing this adverse effect of PPAs. (Tranberg et al., 2020)

4.4. Chaiken et al (2021) with Nash-Cournot analysis on PPAs

This paper conducts theoretical analysis on market efficiency of power purchase agreements in Ohio. The state proposed a partially subsidized PPA-structure between utilities and electricity producers, with a contract of difference (CFD) subsidy system for consumers paying spot-price.

The proposed system would guarantee a minimum price level for renewable energy producers, which in term would pass it down to consumers.

The authors conclude that a subsidized PPA structure will lead to a non-optimal producer pool. The system keeps unprofitable producers in business since they are guaranteed a profit level, whereas otherwise profitable producers are exit the market because they are forced to lower production volume. (Chaiken et al., 2021)

As for the research questions of this thesis, a governmentally incentivized utility PPA structure is likely to lead to statically higher consumer prices, reducing consumer welfare. Inference to corporate PPAs should not however be made, since the studied utility PPAs covered the entire production of wind farms instead of a fixed MW-based volume (as corporate PPAs do).

4.5. Other economics-wise relevant PPA research

Wu and Babich (2012) studied incentive structures in utility PPAs. They found similar results to Chaiken, Duggan Jr et al (2021), inferring that unit-contingent utility PPAs have perverse incentive structure, where intentional misreporting of production volume and schedule can occur. This misreporting is facilitated by production status being producers' private information.

The authors find that such practise increases producers' profits, the burden of which is shifted through utilities to consumers via higher prices.

5. Discussion

Power purchase agreements were likely born out of the issue of insufficient electricity derivatives markets. Compared to other methods of electricity production, renewables' capital-intensive cost structure and exogenous production with near-zero marginal costs made securing future prices valuable. Such value may origin from the riskiness of financing a very new form of production technology, or from the risk aversion of production owners.

PPA off-takers, the buy-side, might have found additional value in the "green" aspect of renewable energy for different purposes. Securing this carbon-free option of the commodity as an intermediate good for production may be another fountain of motivation for buyers.

As a de facto derivatives instrument, unregulated and unscrutinised PPA markets may end up a problem for the rather technically delicate electricity system. Such a problem can arise from the issue of spread covering related demand spikes in a market characterized by a very low near-term price elasticity of demand.

As the share of renewable energy production in the system increases, a large fixed-volume PPA balance could create instability in the general electricity market. This instability might introduce itself as price instability, or, in the worst case, as a need for rolling blackouts, which would both have negative effects on the general utility.

The PPA marketplace is closely linked with the general electricity market. Prices in those markets tend to trend with each other, but high-quality time series data are yet available, due to the newness of PPAs.

Different technical solutions may be introduced to reduce the negative aspects of PPA. Power storage capacity decreases the need for spread covering from the general marketplace. Enhancing production capacity forecasting and reporting capabilities lengthens the reaction time for demand, especially if needs for spread covering are made available for the general market actors.

From the perspective of PPA participants, a price-structure resembling some sort of straddle option strategy may bring spread-covering predictability, with only a small reduction in price stability.

From the perspective of regulators, general marketplace and grid operators, the risks of PPAs can realize later, as their aggregated volume increases. Due to the characteristic of increasing marginal cost in the supply-side of electricity market, spread covering grows the risk for price volatility exponentially.

One efficient way to tackle this risk would be to extend the public, transparent marketplace for electricity derivatives to cover longer lengths and introduce options markets. As the current Nordic market only operates in futures with execution time of < 5 years, such change would bring predictability, flexibility, and thus security to all market actors. History knows many instances of OTC derivatives, such as PPAs, causing problems in even more robust markets due to asymmetric and incomplete information across their operators.

Efficient derivative markets across the globe would diminish renewable production weather risk, which arises from geographically limited diversification. The market operators would likely be international financial institutions, which would result in a globally efficient risk premium level.

Another way to transform the market structure toward more stabile through a favourable incentive structure would be to introduce the standardized fixed price forward contract, or SFPFC by short (Wolak, 2022). Such system would, however, be incompatible with PPAs as they currently stand. Even though the SFPFC system decreases renewable energy producers' opportunities to fix their long-term prices through PPAs, it would transform the whole market toward a higher price stability with increasing share of renewables. Increased price stability would, of course, be favourable for renewable producers as well.

Power purchase agreements are structurally unaligned with desirable characteristics for a good wholesale electricity market design (Wolak, 2021). In the longer term, regulator should strive toward an overall well-designed electricity market where renewable energy producers and purchasers would still be able to hedge future prices. The most efficient way to create such hedging ability would be to implement a transparent derivatives market.

As energy policy plays a large role in tackling climate change, further research on enabling efficient use of renewable energy is needed. The same holds from the ethical standpoint familiar to economic discussion: how to achieve wellbeing and growth globally without resorting to the same carbon-intensive solutions that have landed developed countries where they currently stand.

Future studies in the field of economics are needed especially in electricity market design. In the current electricity system where industrial scale storage is not feasible, a market design that internalizes the inherent problems of renewable energy production is sorely needed.

Specific to PPAs, empirical studies on the general electricity market effects of PPA spread covering are needed. As the phenomenon is still quite new, sufficient data should be collected by the relevant institutions to facilitate such research.

To understand the feasibility of an efficient derivatives market, studying time-correlation of renewable energy production and prices across geography is important. If sufficient evidence is found, introducing a derivatives market would facilitate the diversification of weather-dependent production risk rising from geographically limited market areas. This diversification would likely be efficiently handled by global financial institutions with efficient risk premiums.

6. Conclusion

Power purchase agreements (PPAs) are a sign of fast-developing electricity markets where new, renewable forms of production forms are increasing their share fast, and where optimal risk mitigation measures have not yet surfaced. The larger the share of renewable energy production grows, the more likely market-wide disruptions caused by failed risk allocation.

Economically, this risk arises from the near-zero marginal costs and exogenous production decisions of renewable energy producers. By policy decision, renewable energy is seen as a desirable form of electricity production with less negative externalities compared to the counterfactual solutions. It therefore makes sense to develop the electricity market toward one sufficient for renewable energy producers and consumers.

Currently PPAs serve a critical role in the electricity market for renewable energy producers and consumers. However, as discovered in this thesis, PPAs suffer from numerous issues. Issues occur both between the parties of such a contract, and between contract holders and the general electricity market. The issues could be roughly divided to three categories:

1. Increased general market volatility caused by spread covering
2. Faulty incentive structure between the parties
3. Inefficiencies and possible moral hazards caused by incomplete or asymmetric information about risk

Multiple different solutions could be recommended to handle these issues individually. However, the simplest solution would be to reform the general electricity market to include the idea of the standardized fixed price forward contract (SFPFC), introduced by Wolak (2021); (Wolak, 2022). SFPFC fixes the volumetric risk structure in the general electricity market caused by a growing share of renewable energy.

SFPFC does not, however, fix the risk management issue faced by renewable energy producers. A comprehensive public derivatives market would allow for transparent, efficient risk mitigation by electricity producers. Counterparties such as international financial institutions have the capabilities to carry and geographically diversify the risk currently caused by limited geographic diversification and transmission capacities of individual market areas.

To extend the findings of this thesis and previous PPA literature, empirical research should be conducted into general market effects of PPA spread covering. To understand the feasibility of an efficient derivatives market, studying time-correlation of renewable energy production and prices across geography would be beneficial for the field.

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Appendices

Figures

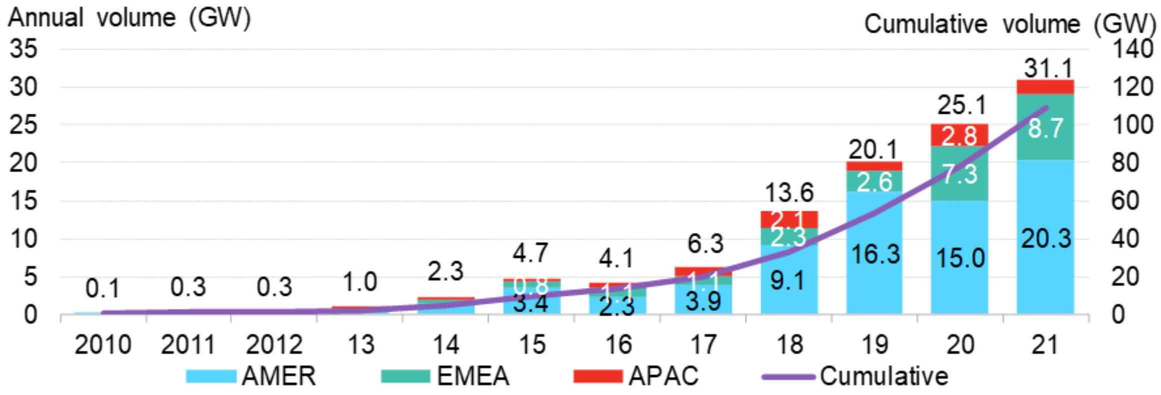


Figure 1 (Henze, 2022)

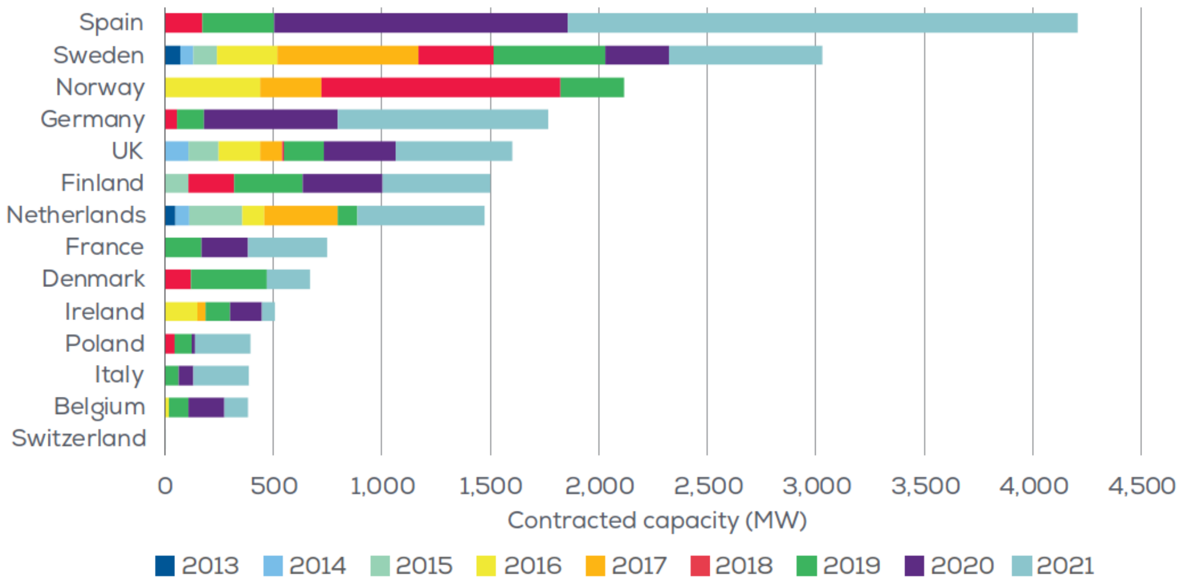
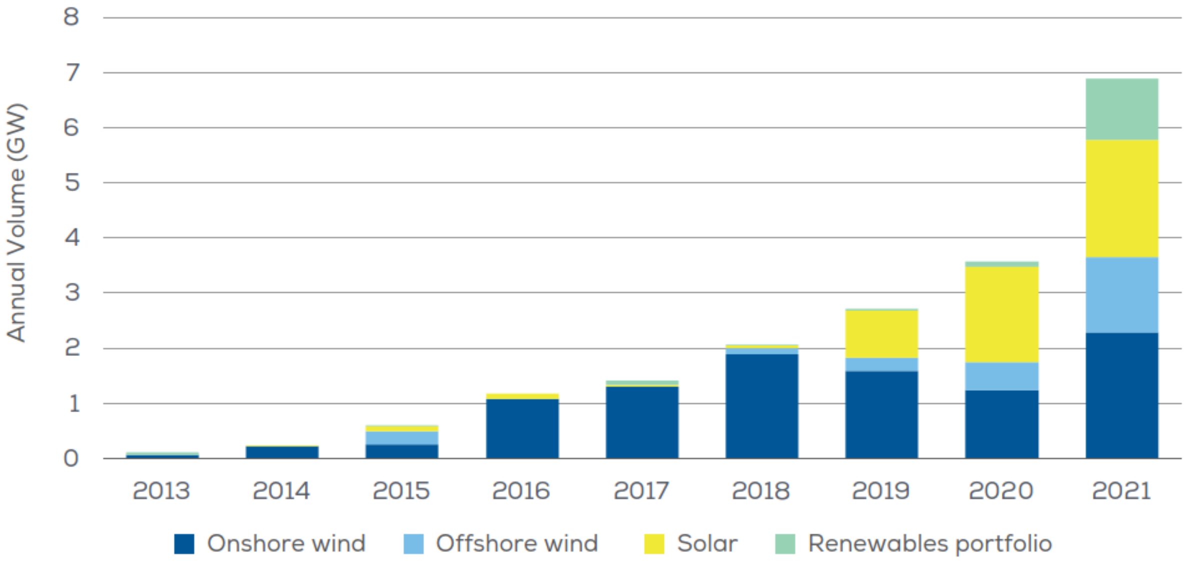


Figure 2 (WindEurope, 2022)



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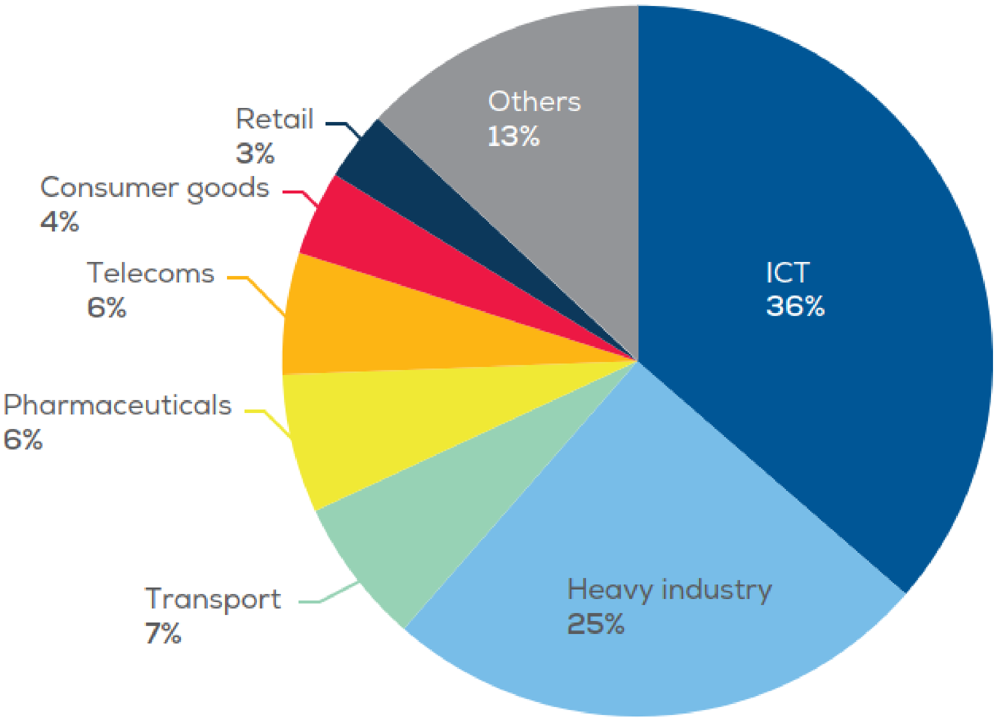

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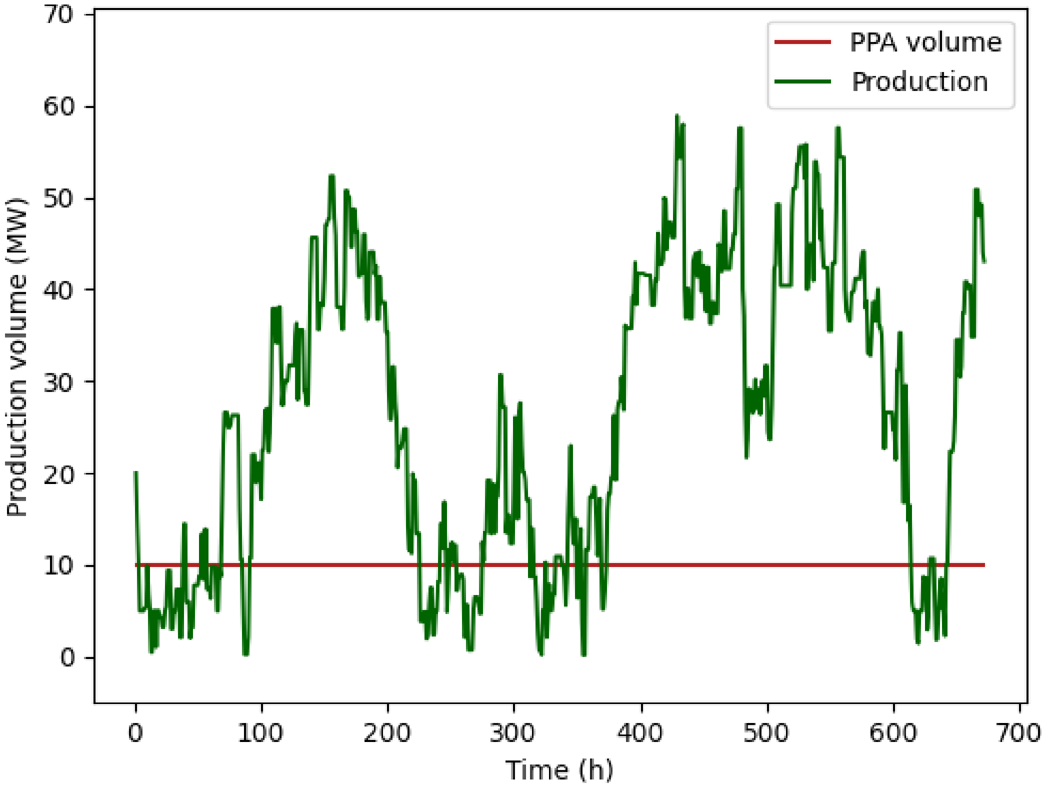


Figure 5: Simulated production of a PPA-tied wind farm

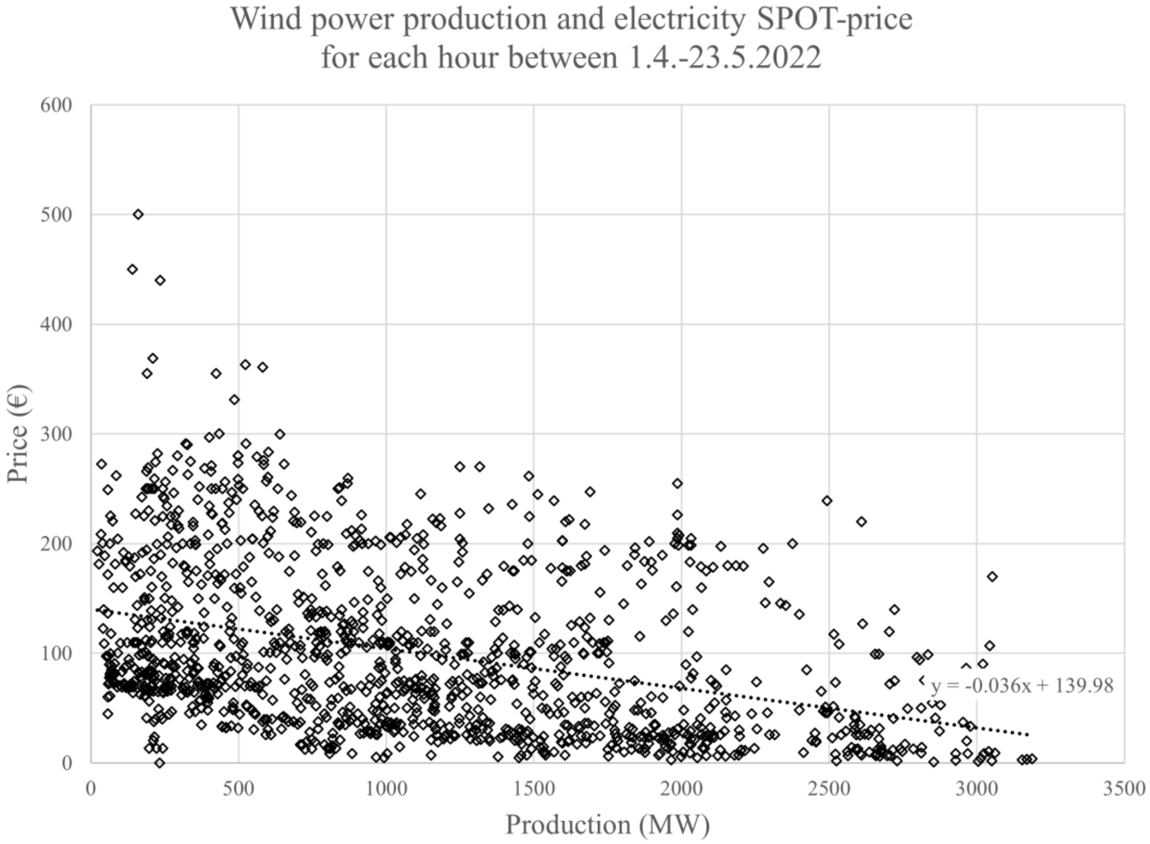


Figure 6: Wind power production and electricity price

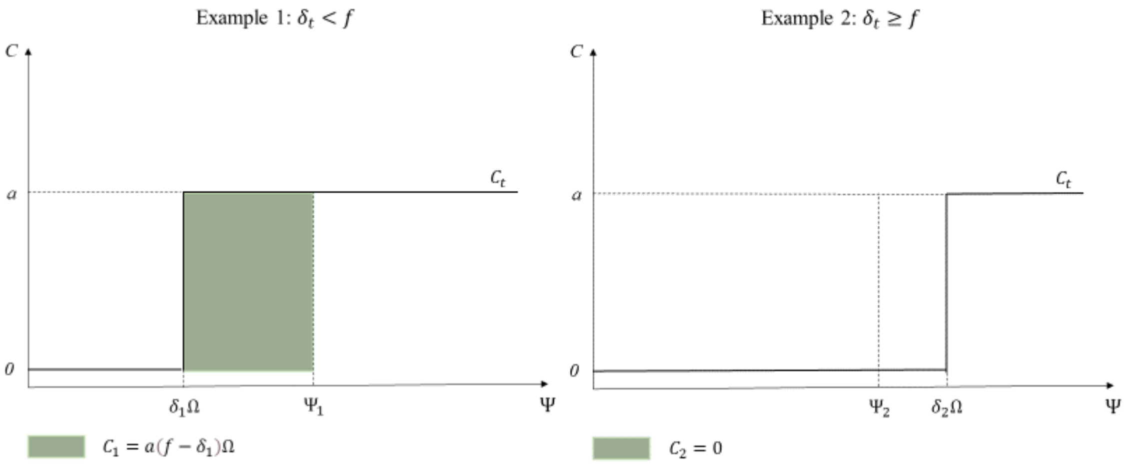


Figure 7: Closed ecosystem cost structure with exogenous production

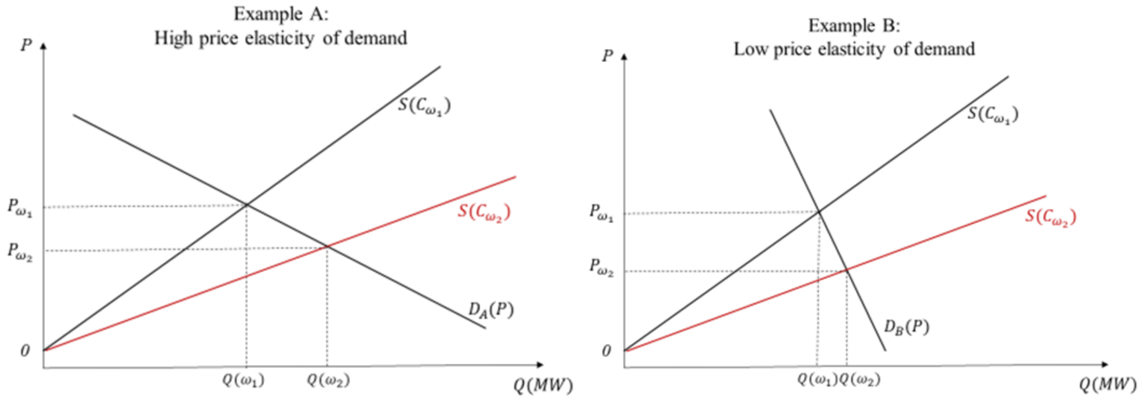


Figure 8: Aggregated market with exogenous supply and spread covering variation

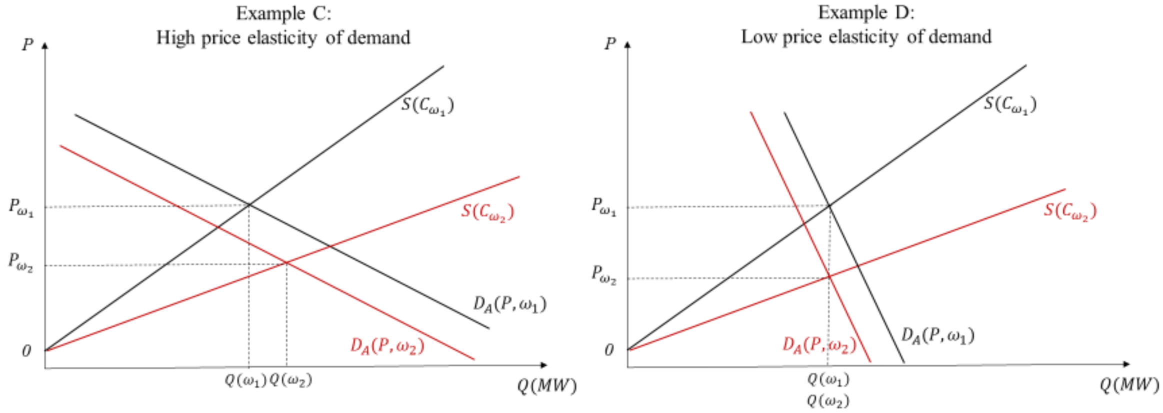


Figure 9: Aggregated market with exogenous supply and spread covering variation

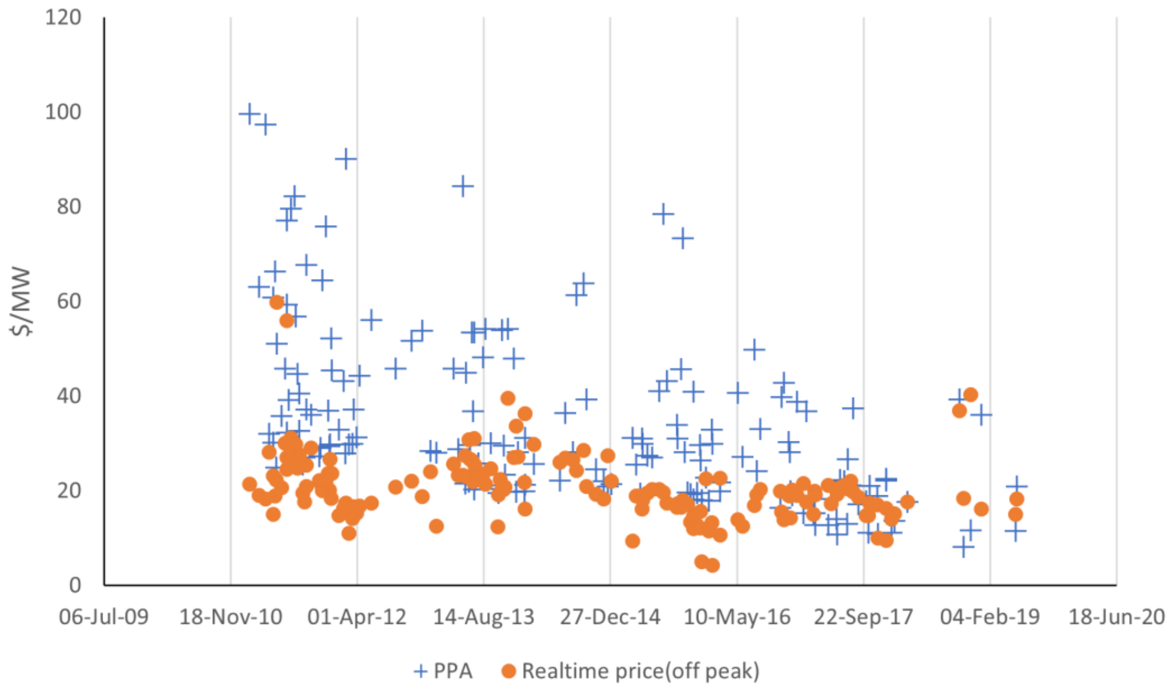


Figure 10 (Baik & Doshi, 2021)

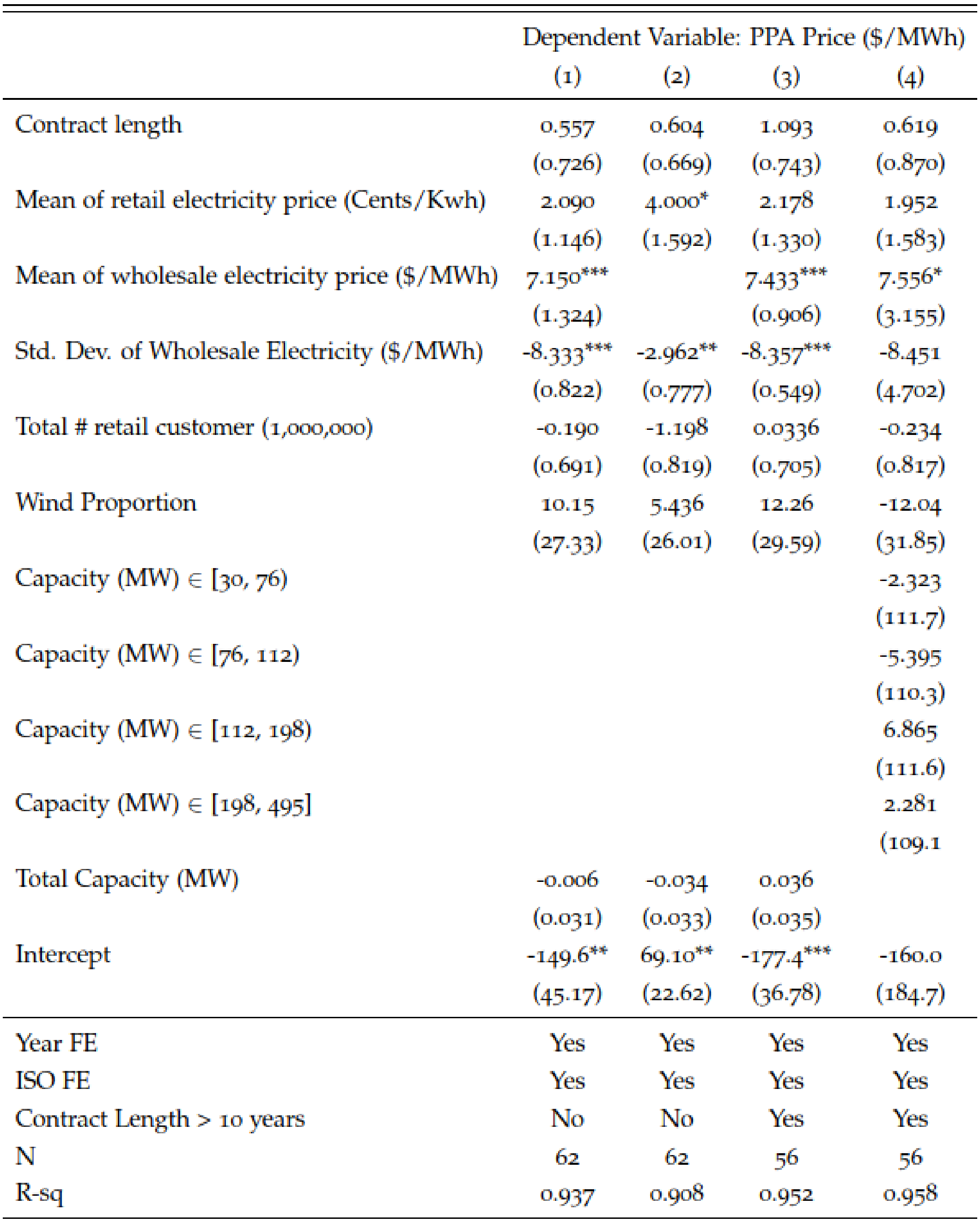
Tables

Table 1, replica of Baik and Doshi (2021)

Table 1: Direction of market participation rate

Participation	Seller	Buyer
Market price	-	+
PPA price	+	-
Price volatility	+	+

Table 2, original from Baik and Doshi (2021)



	Dependent Variable: PPA Price ($/MWh)			
	(1)	(2)	(3)	(4)
Contract length	0.557	0.604	1.093	0.619
	(0.726)	(0.669)	(0.743)	(0.870)
Mean of retail electricity price (Cents/Kwh)	2.090	4.000*	2.178	1.952
	(1.146)	(1.592)	(1.330)	(1.583)
Mean of wholesale electricity price ($/MWh)	7.150***		7.433***	7.556*
	(1.324)		(0.906)	(3.155)
Std. Dev. of Wholesale Electricity ($/MWh)	-8.333***	-2.962**	-8.357***	-8.451
	(0.822)	(0.777)	(0.549)	(4.702)
Total # retail customer (1,000,000)	-0.190	-1.198	0.0336	-0.234
	(0.691)	(0.819)	(0.705)	(0.817)
Wind Proportion	10.15	5.436	12.26	-12.04
	(27.33)	(26.01)	(29.59)	(31.85)
Capacity (MW) ∈ [30, 76)				-2.323
				(111.7)
Capacity (MW) ∈ [76, 112)				-5.395
				(110.3)
Capacity (MW) ∈ [112, 198)				6.865
				(111.6)
Capacity (MW) ∈ [198, 495]				2.281
				(109.1
Total Capacity (MW)	-0.006	-0.034	0.036	
	(0.031)	(0.033)	(0.035)	
Intercept	-149.6**	69.10**	-177.4***	-160.0
	(45.17)	(22.62)	(36.78)	(184.7)
Year FE	Yes	Yes	Yes	Yes
ISO FE	Yes	Yes	Yes	Yes
Contract Length > 10 years	No	No	Yes	Yes
N	62	62	56	56
R-sq	0.937	0.908	0.952	0.958

Notes: This table reports results of the OLS regression of Equation Y. The sample includes wind projects with nameplate capacity larger than 10 MW. Wholesale price is measured by the annual mean of monthly price means (mean of monthly price), the standard deviation of monthly price (variation of the monthly price). Capacity is divided into five quintiles to account for non-linearities in the association between capacity and PPA rates. Robust standard errors clustered at the state-year level reported in parenthesis. Significance: * p<0.05, ** p<0.01, *** p<0.001

Table 3: Results of the intensity equation from the Heckman 2 Step Procedure by Baik and Doshi (2021)

	Dependent Variable: PPA Price ($/MWh)			
	(1)	(2)	(3)	(4)
Contract length	0.640	0.938^{*}	0.588	0.799
	(0.341)	(0.385)	(0.356)	(0.471)
Mean of retail electricity price (Cents/Kwh)	3.388^{**}	4.829^{***}	3.048^{**}	4.046^{*}
	(1.137)	(1.293)	(1.179)	(1.579)
Mean of wholesale electricity price ($/MWh)	5.703^{***}		5.974^{***}	
	(1.449)		(1.490)	
Std. Dev. of wholesale electricity price ($/MWh)	-7.595^{***}	-3.383^{***}	-7.758^{***}	-3.535^{***}
	(1.164)	(0.536)	(1.113)	(0.577)
Capacity (MW) $\in [30, 76)$	-4.046	-15.50		
	(12.06)	(13.02)		
Capacity (MW) $\in [76, 112)$	-20.31	-36.79^{**}		
	(13.30)	(14.22)		
Capacity (MW) $\in [112, 198)$	-10.63	-29.55^{*}		
	(13.35)	(13.91)		
Capacity (MW) $\in [198, 495]$	-14.50	-34.58^{*}		
	(13.49)	(14.03)		
Total Capacity (MW)			-0.039	-0.077^{*}
			(0.025)	(0.031)
IMR ($\hat{\lambda}$)	12.34	22.55^{**}	17.32^{*}	28.67^{**}
	(6.612)	(7.633)	(7.330)	(9.431)
Intercept	-130.2^{**}	29.03	-144.7^{**}	20.27
	(45.70)	(26.16)	(46.42)	(31.60)
ρ	0.847	0.994	0.940	1.000
σ	14.57	22.68	18.42	28.67
ISO FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	508	508	508	508
Wald chi^2	1010.56	807.81	893.73	521.94
prob>chi^2	0.0000	0.0000	0.0000	0.0000

Notes: This Table is the result of the Heckman 2 Step procedure Equation 30. The sample includes wind projects with nameplate capacity larger than 10 MW. Wholesale price is measured by the annual mean of monthly price (mean of monthly price), the standard deviation of monthly price (variation of the monthly price). Capacity is divided into five quintiles to account for non-linearity in the association between capacity and PPA rates. Standard errors in parentheses. Significance: * p<0.05, ** p<0.01, *** p<0.001.